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# CHARACTERISTICS

OF

# EXISTING GLACIERS

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PLATE 1. Frontispiece

The Bishop's Glacier in the Bishop's Range of the Selkirks, with the Purity Range beyond.

*(After a photograph by A. O. Wheeler.)*

# CHARACTERISTICS

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# EXISTING GLACIERS

BY

WILLIAM HERBERT HOBBS

PROFESSOR OF GEOLOGY IN THE UNIVERSITY OF MICHIGAN

"*The present is the key to the past.*" — SIR CHARLES LYELL

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To

PROFESSOR VICTOR GOLDSCHMIDT

OF THE

UNIVERSITY OF HEIDELBERG

A LEADER IN SCIENTIFIC RESEARCH

A GIFTED AND INSPIRING TEACHER

AND A NOBLE AND GENEROUS FRIEND

THIS BOOK IS AFFECTIONATELY DEDICATED

BY

THE AUTHOR

# PREFACE

It has been the common practice to treat the subject of glaciation as if all ice masses having inherent motion of whatever nature were governed by the same laws. Thus the most recent and authoritative work upon the subject has treated the glaciers of Greenland and Switzerland together. The aim of the present work has been rather to emphasize the wide differences in other than dimensional respects which separate such bodies, and to show that the laws which govern their nourishment and depletion, and their reaction with the lithosphere as well, are by no means identical.

The broad line of cleavage is found to lie between those glaciers which completely cover a considerable portion of the rock surface, and have the form of a flat dome or shield, and the remaining types. These latter glaciers being all restricted to mountain districts have been designated mountain glaciers, and they have been found to bear very simple relations to each other, dependent upon the measure of their nourishment and waste. Alimentation being in turn dependent upon climatic conditions, all are brought in order within the cycle of changes which correspond to a period of increasingly rigorous climate followed in turn by more genial conditions — the cycle of glaciation. Throughout the attempt has been to emphasize the broader physiographic elements of the problem and to show the relations to alimentation and depletion.

No attempt has here been made to set forth the views of that school of British geologists particularly which holds that the denudational effect of glacier ice is negative, because it protects the basement from the process of weathering. As will appear from the text, the writer believes that protection from weathering on the cirque floor combined with effective weathering at the base of the cirque wall, explains the lateral migration of the glacial amphitheatre. The doctrine of protection by ice has been given so recent an exposition by an eminent prophet of this school with the expressed approval of his colleagues, that it is believed more is gained from setting forth the evidence from one's own viewpoint than by entering into controversy. Even the names "glacial protection" and "glacial erosion" as applied to the two schools to-day seem inappropriate.

The materials of this volume are three papers which have been published at London, Philadelphia, and Berlin during the year 1910. The first of the series appeared in the *Geographical Journal* under the title "The Cycle of Mountain Glaciation." In a greatly expanded form it is Part I of the present volume. The remaining parts, though originally published in technical journals, were written with a view to their republication in book form, and have in consequence been less altered. Of these the earlier appeared in the *Proceedings of the American Philosophical Society* under the title, "Characteristics of the Inland-ice of the Arctic Regions"; while the concluding part was published a few months later at Berlin in the international journal of glaciology bearing the title, "The Ice Masses on and about the Antarctic Continent." To the Royal Geographical Society of London, the American Philosophical Society of Philadelphia, and the editor of the *Zeitschrift für Gletscherkunde*, the author is under

obligation for permission to republish the papers in their present form. Although they contain original material and of necessity make use of technical terms, it is thought that the language will in the main be intelligible to the general reader as well as to the specialist in glaciology.

Ann Arbor, Michigan,
November 2, 1910.

# CONTENTS

## INTRODUCTION



## PART I

## *MOUNTAIN GLACIERS*

### CHAPTER I

### The Cirque and its Recession



### CHAPTER II

### High Level Sculpturing of the Upland



### CHAPTER III

### Classification of Glaciers based upon Comparative Alimentation

## CHAPTER IV

### Low Level Glacial Sculpture in Moderate Latitudes



## CHAPTER V

### High Latitude Glacial Sculpture



## CHAPTER VI

### Glacial Features due mainly to Deposition



# PART II

## *ARCTIC GLACIERS*

## CHAPTER VII

### The Arctic Glacier Type



## CHAPTER VIII

### Physiography of the Continental Glacier of Greenland

## CHAPTER XIII

### The Marginal Shelf Ice



## CHAPTER XIV

### The Antarctic Continental Glacier where Unconfined



## CHAPTER XV

### The Antarctic Continental Glacier where behind a Mountain Rampart



## CHAPTER XVI

### The Nourishment of Antarctic Ice Masses



## AFTERWORD

## LIST OF PLATES

# ILLUSTRATIONS IN THE TEXT

# CHARACTERISTICS

OF

# EXISTING GLACIERS

# CHARACTERISTICS OF EXISTING GLACIERS

## INTRODUCTION

**The Ancestry of Glacial Theories.** — If we are to gauge the generally accepted hypotheses of any science and arrive at individual conclusions respecting their value, we must be prepared to inquire into the ancestry of each — we must trace out the route by which each has come to its present position of eminence. It is a Scriptural saying that "we see through a glass darkly," and scientific reasoning, we know, makes a demand upon the imagination. To a solid basis of observation, which at best but half discloses the truth, inductive reasoning is to be added if science is to advance.

Psychological processes and the tendencies of scientific thought are thus to be well considered by the more thoughtful student of science in forming his opinions. Experience has shown that whenever a new and more advanced viewpoint has been gained to take the place of an earlier one, and its superiority has come to be acknowledged, the tendency has always been to sketch in from that one standpoint even the more distant objects, rather than to move forward to new and independent positions. This has been no less true of glacier study than of the broader divisions of science. This general fact is, perhaps, in part to be explained by the optimism inherent in human nature; but account must also be taken of the authority of a great name in science.

With the multiplication of workers which is characteristic of present-day science, the number of authorities increases and the servile attitude within the profession toward its great leaders will gradually disappear. The student of geology would, however, do well to take note of the early dominant influence of Werner or von Buch in Germany, of de Beaumont in France, of Murchison in England, or of Agassiz, the "Pope of American Science."

It is a truism that the influence of things seen is more potent than that of things merely heard of or read about. The unconscious effect of the immediate environment, of oft present scenes, in directing the trend of thought, and of determining convictions, is an unwritten chapter in the philosophy of science. It would be easy to show how all the accepted views of geological processes would have been different had the seats of learning been located either in the tropics or in polar, rather than temperate, latitudes. Moreover, it has not always been easy to say what observed phenomena are of general and what are of only local importance. Environment is, therefore, of the utmost importance in the evolution of the "body of doctrine" of any science.

To apply these considerations to glacial theories, we find that whereas existing glaciers are found in all latitudes, but with the largest and most important types in polar and sub-polar regions; the earliest and by far the largest number of studies have been made in the Alps, where a single type of small glacier is found. The reason is not far to seek. The Alps have now for a good many years been the playground of Europe easily reached and explored by her scientific men.

Until the close of the eighteenth century there existed a popular belief that the mountain highlands were bewitched. The Alps were the *montagnes maudits* and in consequence a *terra incognita.* It was de Saussure who both by precept

and example as well as by offering a generous prize, stimulated interest in exploring the Alps and thus dispelled the illusions which had so long clung to them. We may here pass over his scientific conclusions, as we may over those of Scheuchzer, Hugi, Venetz, and other early workers, important as they were; for it was not until the early forties of the nineteenth century when Agassiz[1] and Charpentier[2] published their important monographs upon the physiography, the structure, the mechanical work, and the former extensions of the Alpine glaciers, that a lively interest was excited in them.

This sudden interest in glaciers on the part of geologists arose, not so much because of an interest in the Alpine glaciers themselves, as for the reason that on the basis of these studies Agassiz soon founded his theory of the ice age, and was thus for the first time able satisfactorily to explain the origin of the erratic blocks which are found strewn over the Alpine foreland, the North German plain, the British Isles, and Northern North America. The great continental glaciers which he thus hypothecated were from a thousand to a millionfold greater than those ice masses which had been seen and studied, from which ice masses they must have differed most widely. This is particularly true, as we now know, as concerns their physiographic development and their alimentation. No continental glaciers being then known, it was but natural that the attributes of Alpine glaciers should have been carried over to the continental type thus reconstructed in imagination upon the basis merely of its carvings, its gravings, and its deposits.

It is one of the strange coincidences of science that almost at the moment when the epoch-making studies of Agassiz were being made upon Swiss glaciers, three great scientific exploring expeditions were independently discovering the greatest of existing continental glaciers, that of Antarctica, but with-

out being able to set foot upon it or to learn aught of its characters. Thus it happened that the views concerning continental glaciers took shape before any had been visited, and one result is that even to-day in university and college texts we find the attributes of continental, Alpine, and other glacier types classified together as though all were necessarily identical in origin.

The first attempt to arrive at observational knowledge of "inland-ice" was the expedition of Otto Torell to Spitzbergen in 1858. It was the unsuccess of the Swedish polar expedition of 1872–1873 which made the journey by Nordenskiöld and Palander across Northeast Land (Spitzbergen) the first successful, comprehensive attempt to observe any considerable area of inland-ice. It will, however, hardly be claimed that the results of this expedition are well known, or that they have in any important way influenced glacial theories. The later discoveries of Nordenskiöld, Nansen, and above all Peary on the great continental glacier of Greenland, rich as they are in results, are, moreover, not as well known as they should be, and are only beginning to modify the views held concerning continental glaciers. In fact, it is only toward the beginning of the twentieth century that former continental glaciers have begun to be studied on the basis of any other model than the Alps.

**The Factor of Air Temperature.** — With the advance of knowledge concerning the sequence of conditions affecting glaciers, it has come to be quite generally recognized that for any given district the factor of supreme importance in initiating glaciation is temperature; a very moderate change in the average annual temperature being sufficient to transform a district, the aspect of which is temperate, and to furnish it with snow-fields and mountain glaciers. Thus it has recently been estimated that a fall of but 3° F. in the average annual temperature of Scotland would result in the

formation of small glaciers within the area of the Western Highlands, while a like fall of 12° F. within the Laurentian Lake district of North America would be sufficient to bring on a period of glaciation.

It is further of interest that such temperature changes affect the distribution of air pressure over the continents and in this or in other ways directly modify the precipitation of moisture. Statistics have shown that cold periods correspond to high precipitation and warm periods to smaller falls of snow and rain.[3] It is further found that the larger climatic changes are common to very large areas of the earth [4] and are probably world wide in their extent.[5]

In climates such as now prevail on the borders of Antarctica, it is true that most of the snow falls in the warmer season. Gourdon has apparently been misled by this into believing that warm rather than cold climates promote glaciation.[6] As we shall see, glaciers are under these conditions nourished by a different process, which is in a large measure independent of local evaporation.

With the probability that such progressive climatic changes would be initiated slowly,[7] the first visual evidence of the changing condition within all districts of accentuated relief would probably be a longer persistence of winter snows in the more elevated tracts; which accumulation of snow would eventually contribute a remnant to those of the succeeding winters, and so bring on a period of glaciation. Such a change of air temperatures with resultant changes in snow precipitation may be otherwise expressed as a depression of the *snow-line* of the district. All are familiar with the fact that as we ascend in the atmosphere we pass into successively colder strata. Mountains which even in tropical regions push up their heads to great altitudes, are in consequence capped with snow throughout the year. The snow-line is the lower limit of this "perpetual" snow, and it is

evident that any refrigeration of the atmosphere will cause the line to descend toward the lower levels.[8]

From this beginning the process is an advancing one until a culmination of glaciation is attained corresponding to the most rigorous of the climatic conditions. A resumption of a more genial climate would bring about a reverse series of changes, a waning of the glaciers setting in so soon as the winter's fall of snow is insufficient to contribute a remnant to succeeding seasons. It is, therefore, proper to speak of *advancing* and *receding hemicycles of glaciation*.[8a]

This use of the expression *cycle of glaciation* carries with it no idea of lapse of time except such as is implied in the completion of a progressive series of climatic changes, and a return to the initial condition. In any given district the time may have been insufficient to accomplish the complete normal series of denudational results indicated in neighboring districts which were more favored in respect to glacier nourishment. The term "cycle of glaciation" is, therefore, not the equivalent of "glacial cycle" used by Professor Davis,[9] since in our use the cycle is measured in climatic changes rather than in the attainment of certain denudational effects within the glaciated valleys. Russell's earlier discussion of the "Life History of a Glacier"[10] takes account of this alternation of sequential climatic changes — a climatic episode — with resultant changes in the size and physiographic forms of glaciers.

**Mountain *versus* Continental Glaciers.** — Those glaciers which are developed in mountain districts differ from the ice masses of the interiors of continents or islands in several important particulars. As respects their physiographic forms, they are as different as possible.[11] Inland-ice assumes a form the visible surface of which is largely independent of the basement upon which it rests, while there is no definite model to which the glaciers of mountains conform, they

being moulded with reference to the irregularities of their beds. *It is characteristic of inland-ice that no portion of the lithosphere is exposed above its higher levels. The glaciers of mountains, on the contrary, always have rock exposed above*

FIG. 1. — Ideal section across inland-ice.

*their highest levels.* The physiographic form assumed by inland-ice is invariably that of a flat dome or shield, and all visible projections of the lithosphere within the area of the ice are restricted to the marginal zone (see Fig. 1). The glaciers of mountains, as already stated, conform to no definite model, and rock projections may appear at any level, *but are always to be seen above the highest levels* (see Fig. 2 and pl. 1).

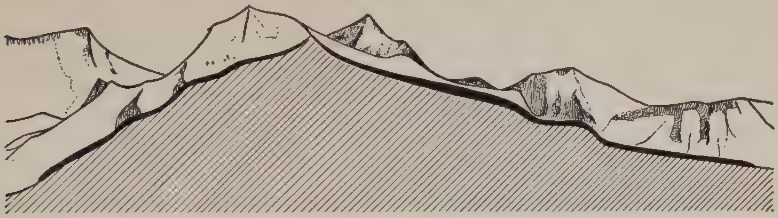

FIG. 2. — Section across a mountain upland occupied by glaciers with the glaciers in black (after Hess).

The unique exception to this law is the small ice-cap or plateau glacier which is transitional between inland-ice and mountain glaciers (see Fig. 3). In size more nearly allied

FIG. 3. — View of the ice-cap of the Eyriksjökull, Iceland, seen from the West (after Grossman [12]).

to the glaciers of mountains, in form the ice-cap resembles the masses of inland-ice — it is developed as a flat dome or

shield. As regards the processes by which they are nourished, ice-caps are, however, as will be seen, quite different from true inland-ice; and they should in consequence be considered separately and in order between the others, so as to call attention to their intermediate position. Their size is usually a direct consequence of the limitations of the circumscribed area of the rock platform upon which they rest — usually either a small island or a limited portion of a high plain or plateau. *The regular surface form common to inland-ice and ice-caps is due to the fact that the irregularities of the base are small when compared with the dimensions of the ice mass.* The ice-caps of Norway or Iceland have in common with the glaciers of mountains, a considerable elevation above the sea, but the variations of their base from a horizontal plane are small by comparison with the other dimensions. Curiously enough there is to this rule a single exception, and here it is not the flatness of the base but the precipitousness of platform slope which is the determining factor. This special case is of ice-caps on the high volcanic peaks of low latitudes, which on excessively steep slopes push their summits far into the upper atmospheric strata.

**Low Level *versus* High Level Sculpture.** — In part the failure to note the essential difference between mountain glaciers and inland-ice is due to the peculiar evolution of glacier studies which has been outlined in the introduction, but in part it is to be explained by a rather general tendency to treat the subject of erosion by glaciers in mountains from studies made especially in the lower altitudes.[13] A quite general neglect of those special conditions of denudation which are operative in high-level areas of glaciers is, it is believed, responsible for an over-emphasis laid upon the U-shaped trunk valley and the hanging tributary valley, important as these features are.[14] This over-emphasis can, perhaps, be best illustrated by reference to a series of three

successive idealistic sketches, executed with great skill by an eminent American geographer, and intended to develop especially the erosion forms which result from mountain glaciers.[15] The low-level sculpturing expressed by these sketches is, in the opinion of the writer admirable and a true rendering of nature. It is the failure to recognize any additional process of erosion operative in higher altitudes which destroys the value of the high-level sculpturing displayed.

So far as low-level mountain glaciation is concerned, the erosive processes are pretty well understood to be identical with those of continental glaciers, namely, abrasion and plucking. The former process is a wearing away of the rock surface which is in every way analogous to the abrasion of a facet upon a gem by a lapidary, the stones frozen into the mass of the ice corresponding to the diamond dust imbedded in the lap. The product of glacial abrasion is rock flour. The plucking process, on the other hand, is a removal of the rock in larger masses aided often by the fracture planes already present, which so often bound the dislodged masses. In parts of a glacier bed recently uncovered near the glacier foot, the dislodged blacks may sometimes be fitted into the rock floor from which they have been extracted.[16] With respect to the direction of movement of the ice, abrasion is particularly developed on obstructing rock masses on the side from which the ice comes — stoss side, and plucking upon the side away from which it moves — the lee side. The two sides of an obstruction in the bed have therefore been called the "scour" side and the "pluck" side.[17] The plucking process is no doubt in some cases much facilitated by a ready separation of the rock along planes parallel to the surface, these planes being due to the strains set up in the rock parallel to its free surface.

To these processes of abrasion and plucking there is in the

case of mountain glaciers a third important denuding process which may locally be more important than both the others acting together. It is this process of head-wall erosion which as regards reaction with the lithosphere differentiates all types of mountain glaciers from continental ones. This distinguishing process is responsible for the development of the *cirque* (Ger. *cirkus*), which is known by a variety of names in different glacier districts. In Scotland it has been generally referred to as the *corrie*, in Wales as the *cwm*, and in Scandinavia as the *botn* or *kjedel* (*kessel*). In the scientific literature of the subject the Bavarian-Austrian word "kahr" has been used with increasing frequency for the same topographic feature.

In view of this diversity in resultant topography, and despite their close genetic relationships, we would do well to sharply separate in our discussions continental glaciers from the other types, which latter we may include under the broad term of "mountain glaciers."

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[5] Frank Leverett, "Comparison of North American and European glacial deposits," *Zeitsch. f. Gletscherk*, vol. **4**, 1910, pp. 241–316.

[6] "It is in fact the proportion of water vapor in the air which controls the greater or less abundance of snow precipitation, so that, as Tyndall has remarked, it is the solar action which is necessary to bring on the initial condition; the conclusion, which appears paradoxical at first, is the following, that the warmest periods determine more active evaporation of the ocean water; it is to them that the greatest extensions of glaciation correspond. Cold plays the merely passive rôle of condenser." (Gourdon, *Expéd. Ant. Franç.*, 1903–1905, *Glaciologie*, 1908, p. 70.)

[7] I. C. Russell, "Climatic Changes indicated by the Glaciers of North America," *Am. Geol.*, vol. **9**, 1892, p. 336.

[8] A. Penck, "Climatic Features of the Pleistocene Ice Age," *Geogr. Jour.*, vol. **27**, 1906, pp. 182–187.

[8a] William Herbert Hobbs, "The Cycle of Mountain Glaciation," *Geogr. Jour.*, vol. **36**, 1910, pp. 146–163, 268–284, 36 figs.

[9] W. M. Davis, "Glacial Erosion in France, Switzerland, and Norway," *Proc. Bos. Soc. Nat. Hist.*, vol. **29**, 1900, pp. 294–300.

[10] I. C. Russell, "Glaciers of North America," 1897, pp. 190–206.

[11] E. v. Drygalski says: "The difference between glaciers and inland ice is essentially a quantitative one. Glacier forms are small, inland ice masses great glaciations. . . . Inland ice masses are ice overflows of entire earth surfaces, glaciers are branching outflow systems for snow deposits guided by the features of the earth's surface." In Keilhack's "Lehrbuch der praktischen Geologie," 1908, p. 269.

[12] Karl Grossmann, "Observations on the glaciation of Iceland," *Glacialists' Magazine*, vol. **1**, No. 2, 1893, pl. 3, fig. 2.

[13] "The visitor replied that he was a valley climber, not a mountain climber. He found sufficient pleasure at the mountain base, and such was my case also. Mountain tops are indeed worthy objects of a climber's ambition, but if one wishes to get at the bottom facts, let him examine the valleys." (W. M. Davis, "Glacier Erosion in the Valley of the Ticino," *Appalachia*, vol. **9**, 1901, p. 137.)

[14] On hanging valleys, see especially W. M. Davis, *Proc. Bos. Soc. Nat. Hist.*, vol. **29**, 1901, pp. 273–322; and G. K. Gilbert, "Glaciers," *Harriman Alaska Expedition*, vol. **3**.

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# PART I

## MOUNTAIN GLACIERS

## CHAPTER I

### THE CIRQUE AND ITS RECESSION

**The Glacial Amphitheatre in Literature.** — It is safe to say that no topographic feature is more characteristic of the mountains which have been occupied by glaciers than is the cirque. Approaching a range from a considerable distance, there is certainly no feature which so quickly forces itself upon the attention. The U-shaped valley and the hanging side valley, important as these are, are here decidedly less impressive. Yet the great majority of works upon the subject, by ignoring the significance of the cirque, allow the reader to assume that the glaciers discovered the cirques ready formed to gather in the snows for their nourishment. Even the standard work of Chamberlin and Salisbury is open to this objection.[1]

Despite the attitude of the general texts, which so largely determine what might be called the accepted body of doctrine of a science, there are a number of papers dealing with the origin of the cirque. One of the first to recognize the cirque as a product of glacial erosion was Tyndall, whose keen mind has so illumined the page of mountain glaciation.[2] In opposition to his view, Bonney published in 1871 a somewhat elaborate article, in which the line of argument was: (1) that the Alpine cirques must have been produced by the agency

which shaped the valleys below them; (2) that the valleys were not moulded by glaciers; and hence, (3) the cirques must have been retained from the pre-glacial land surface.[3] The published discussion of this paper developed no opposition to the view, though Doctor, now Sir Archibald, Geikie stated that he could not see his way to account for the vertical walls surrounding the cirque. On the other hand, the Italian Professor Gastaldi recognized the work of the ice in the shaping of cirques in the Italian Alps,[4] as Helland did in those of Norway. The latter believed that excessive weathering in the rock above the *névé* played an important rôle, though abrasion by the ice upon the floor was the larger factor.[5] Later Russell in America,[6] Wallace in England,[7] and de Martonne upon the continent,[8] further advocated the glacial origin of cirques. Penck has explained the development of cirques as the result of sub-glacial weathering — alternate thawing and freezing — beneath glaciers during the incipient stage particularly ("hanging glaciers").[9] This eroding process, he considered, would be greatest toward the middle of the glacier, so that the original concavity of the slope beneath it would be more and more deepened. It must be evident that this explanation does not properly account for the steepness of the cirque walls, which it will be remembered could not be accounted for by Geikie.

Attention was again directed to the process of cirque shaping by an important paper of Richter's published in 1896.[10] His studies having been made in Norway, where a country rounded and polished by the continental glacier had been only partly invested by mountain glaciers, the cirques from the latter formed individual "niches" in the uplands. Following Gastaldi, the form of these niches was happily likened to that of an armchair (see Fig. 4).[11] Richter observed that the steep walls of the cirque were the only surfaces unglaciated, and hence he concluded that they were not to be

ascribed to ice-abrasion, but to weathering. The moulding of the cirque floor he ascribed to abrasion, and, referring to the cirque walls, said —

> The material loosened by weathering is removed by the glacier or slides off over the *névé* to form either actual moraines, or, at least, *névé* moraines. These walls do not bury themselves in their own *débris*, and in consequence continually offer fresh surfaces for attack. Finally, the wearing away of the cirque floor by the glacier coöperates to keep the cirque walls on a steep angle and facilitates avalanching.

FIG. 4. — Cirque excavated in the glaciated surface of Norway, Northern Kjedel on Galdhöpig (after E. Richter).

In a more extended and later paper,[12] treating especially the formation of cirques, Richter has explained that his view differs from that of Helland only in ascribing greater importance to weathering upon the cirque walls and less to abrasion upon the cirque floor. Inasmuch as the excessive weathering of cirque walls, as maintained by Richter, is *above* the surface of the *névé*, a horizontal plane of denudation should develop at that level. No evidence of this plane being discovered, its absence is explained by Richter through abrasion from the snowbank which would collect upon it so soon as formed. This is the fatal weakness of the Richter hypothesis.

**Relation of Cirque to Bergschrund.** — Up to the beginning of the twentieth century, as we have seen, few geologists had

greatly concerned themselves with the erosion conditions at high levels, the work of Richter being on the whole the most comprehensive. The whole subject of cirque erosion was rather generally ignored, as it is, indeed, to-day. Sir Archibald Geikie, referring to the corries of the Scottish Highlands,[13] wrote —

> The process of excavation seems to have been mainly carried on by small convergent torrents, aided, of course, by the powerful coöperation of the frosts that are so frequent and so potent at these altitudes. Snow and glacier ice may possibly have had also a share in the task.

Writing in the same year, Reusch ascribed the Norwegian cirques to the action of surface water descending through the crevasses over falls in the continental glacier which, in Pleistocene times, overrode the country;[14] and the following year Bonney reiterated his view that cirques were the product of water-erosion.[15] Only a few years before, Gannett had curiously explained the origin of cirques through the wear of avalanched snow and ice upon the cirque floor, likening the erosive process to that which takes place beneath a waterfall.[16]

The discovery of the method by which the glacier excavates its amphitheatre must be credited to a keen American topographer-geologist, Mr. Willard D. Johnson of the United States Geological Survey.[17] In fact, to him and to another American topographer, Mr. François E. Matthes, we owe the most of what is known from observation concerning the initiation and development of the glacier cirque. Reasoning that abrasion was incompetent to shape the amphitheatre, Johnson early surmised that the great gaping crevasse which so generally parallels the cirque wall and is termed the *Bergschrund* (Fr., *rimaye*) went down to the rock beneath the *névé*, and that it was no accident that glaciated mountains alone " abound in forms peculiarly favorable to snow-

drift accumulation" (see Fig. 5). These observations were made as early as 1883, and in order to test his theory, John-

FIG. 5. — Bergschrund below cirque wall on a glacier of the Sierra Nevada, California (after Gilbert).

son allowed himself to be lowered at the end of a rope 150 feet into the Bergschrund of the Mount Lyell glacier until he reached the bottom. He found a rock floor to stand upon, and rock extended up for 20 feet upon the cliff side. We may here quote his terse sentences, since too little attention has been accorded this important observation.[18]

The glacier side of the crevasse presented the more clearly defined wall. The rock face, though hard and undecayed, was much riven, the fracture planes outlining sharply angular masses in all stages of displacement and dislodgment. Several blocks were tipped forward and rested against the opposite wall of ice; others quite removed across the gap were incorporated in the glacier mass at its base.

Everywhere in the crevasse there was melting, and thin scales of ice could be removed from the seams in the rock. The bed of the glacier, elsewhere protected from frostwork, was here subjected to exceptionally rapid weathering. *By maintaining the rock wall continually wet, and by admitting the warm air from the surface during the day, diurnal changes of temperature here resulted in very appreciable mechanical effects, whereas above the névé only the seasonal effects were important.*

This observation of Johnson is, it will be observed, in contrast with the suppositions of Richter, who believed that the maximum sapping upon the cirque wall occurred *above* the surface of the *névé*. The function of the Bergschrund, which separates the stationary from the moving snow and ice within the *névé*, is thus found to be of paramount importance in the shaping of the amphitheatre.

With the coming of winter this process halts and the Bergschrund fills with snow, but the following spring it again opens, though always a little higher up and nearer to the cirque wall. In this way the blocks excavated from the base of the wall are the more easily transferred to the moving portions of the glacier.[19]

**The Schrundline.** — That a sharp line is observable in abandoned cirques separating the accessible from the non-scalable portions of the wall, has been pointed out by Gilbert, who has given his support to the view of Johnson, and confirmed it by observations of his own[20] (see Fig. 6). Penck, on

Fig. 6. — Schrundline near Mt. McClure in the Sierra Nevadas of California. Above the Schrundline it is too steep for snow to rest, and the drifts are accordingly below this level (after Gilbert).

the other hand, the following year revived the view of Richter that excessive sapping occurs upon the cirque walls *above* the *névé* surface,[21] though he calls in the Bergschrund in order to gather in and remove the rock fragments which fall from the cliff.[22]

**Initiation of the Cirque, Nivation.** — Johnson's studies upon the processes of cirque shaping, had shown how a nearly perpendicular cirque wall is steadily cut backward through basal sapping at the bottom of the Bergschrund. The problem of how the snowbank, which was the inevitable forerunner of the glacier, had transformed the relatively shallow

depression which it presumably discovered into the steep-walled amphitheatre, he did not attempt to solve. Yet the nourishing catchment basin is a prerequisite to the existence of the normal glacier. The solution of this problem has been suggested by another American topographer, Mr. F. E. Matthes.[23] In the Bighorn mountains of Wyoming he has found exceptional opportunities for this study. Owing to the low precipitation within the region and the consequently inadequate nourishment of glaciers, a large part of the pre-glacial surface still remains. There is, therefore, represented within the district every gradation from valleys which were occupied by snow during a portion only of the year to those which were the beds of glaciers many miles in length. Both small glaciers and high-level drifts of snow still remain in a number of places.

Mr. Matthes has demonstrated that the snowbanks without movement steadily deepen the often slight depressions within which they lie by a process which he has called "nivation" — excessive frost-work about the receding margins of the drifts during the summer season. The ground being continually moist in this belt due to the melting of the snow, the water penetrates into every crevice of the underlying rock, so that it is rent during the nightly freezing. Rock material thus broken up and eventually comminuted, is removed by the rills of water from the melting snow.[24] By this process the original

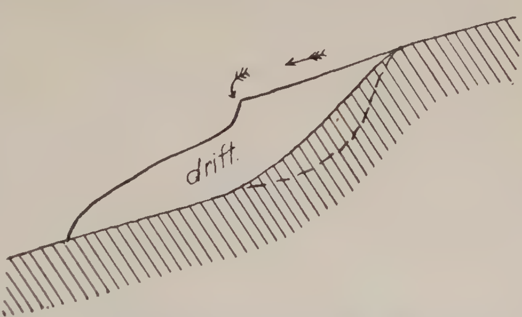


Fig. 7. — Cross section of a snowdrift site on a slope showing formation of niche by nivation (after Matthes).

depression is deepened, and, if upon a steep slope, its wall becomes recessed (see Fig. 7).

The occupation of a V-shaped valley by snow, as Matthes has further shown, tends through the operation of this process to transform it into one of U-section, since the weathered rock material upon the slopes is transported by the rills and deposited upon the floor. All gradations from nivated to glaciated forms are to be found in the Bighorn range.

During the field season of 1909 the writer took the opportunity to examine *névé* regions and high-level snowbanks in a number of districts, with the result of confirming the importance of the nivation process as outlined by Matthes. In plate 2 A and B are shown two snowbanks which were photographed on July 25 near the summit of Quadrant mountain, in the Gallatin range of the Yellowstone National Park. The gently sloping surface of this mountain represents the pre-glacial upland unmodified by Pleistocene glaciation. Though between 9000 and 10,000 feet above sea, it supports a rich herbage, and is a favorite grazing-ground of the elk. In A of plate 2 the snow bank is seen surrounded by a wide zone within which no grass is growing, but where a finely comminuted brown soil is becoming a prey to the moving water. B of plate 2 exhibits another bank lying in the depression which it has largely hollowed. At its lower end (at the left) is seen an apron of fine brown mud deposited by the overburdened stream as it issues from beneath the drift.

Later the writer has had in Swedish Lapland opportunity to observe the results of the nivation process under exceptionally favorable circumstances. Here in place of a preglacial surface, such as has been dissected in the American mountain districts already described, the surface of the country has been planed down to softly rounded knobs of rather large scale under the influence of the mantling con-

*A.* Summer snowbank surrounded by brown border of finely comminuted rock. Quadrant Mountain, Y.N.P.

*B.* Snowbank lying in a depression largely of its own construction. Note stream outwash of fine mud at the left. Quadrant Mountain, Y.N.P.

tinental glacier of Pleistocene time. Subsequent to this general planation the higher areas have in favorable situations been occupied either by mountain glaciers or by more or less persistent snow-drifts. The drift sites are found upon the hillsides as distinct niches in which the characteristic "arm-chair" form of the incipient cirque is already apparent. It is the scale particularly which distinguishes them from glacial amphitheatres (see Fig. 8). It is of great interest to find

FIG. 8. — The characteristic form of drift sites on hillsides in Swedish Lapland. The form of the cirque is already discernible. On the floor a division into hexagons indicates that the process of solifluction has played an important part. (After a photograph by G. W. v. Zahn.) [25]

that the quite remarkable but as yet little understood process of rock flow (solifluction) has here played an important part in shaping the incipient cirque. The floors of the drift sites are in some instances at least divided into the hexagonal pattern so characteristic of soil flow on relatively

flat surfaces.[26] Inasmuch as it is now recognized that melting snow is the immediate requisite for effective solifluction, it is apparent that this process in some of its phases at least is clearly allied to the process of nivation.

An interesting question is at what point the snow-field or *névé* will, by taking on a motion of translation, assume the functions of a glacier. At this stage of transition the Bergschrund should first make its appearance. Comparison of nivated and glaciated slopes in the Bighorn mountains led Matthes to think that upon a 12 per cent. grade the *névé* must attain a thickness of at least 125 feet before motion is possible. Another possible method of approaching this problem has suggested itself to the writer. In mountains like the Selkirks, with steep slopes terraced by the flatly dipping layers in the rock, a peculiar type of small cliff glacier is nourished high above the larger snow-fields of the range and avalanched upon the lower shelves so as to leave vertical sections open to study (see plate 3 A). Perhaps because of their small size these cliff glaciers have not developed cirques, though a Bergschrund parallels the generally straight headwall. Examined through a powerful glass, the snow in the lower layers can be seen to have lost its brilliant whiteness, though it does not yet appear as ice. A number were examined with a view to determine the approximate minimum thickness of the glacier, but all exceed the minimum estimate of Matthes by at least 100 feet. This is not regarded as in any way discrediting his figure, but rather as suggesting the possibility of more thorough examination along the same line.

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[19] I. C. Russell, "Glaciers of North America," 1897, p. 193.

[20] G. K. Gilbert, "Systematic Asymmetry of Crest-lines in the High Sierras of California," *Jour. Geol.*, vol. **13**, 1905, pp. 579–588. See also E. C. Andrews, *ibid.*, vol. **14**, 1906, p. 44.

[21] Many European glacialists and among them apparently Garwood (*Geogr. Jour.*, vol. **36**, 1910, p. 313), have failed clearly to understand that the basal sapping occurs *at and near* the base of the Bergschrund.

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[23] François E. Matthes, "Glacial Sculpture of the Bighorn Mountains, Wyoming," *21st Ann. Rept. U. S. Geol. Surv.*, 1899–1900, pp. 167–190.

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[25] The structure of the pavement in the foreground has been added from another photograph.

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## CHAPTER II

### HIGH LEVEL SCULPTURING OF THE UPLAND

**The Upland[1] dissected.** — Having obtained a clear conception of the process of head-wall erosion through basal sapping, Johnson was in a position to account for the topography which he encountered in the High Sierras of California. This topography is best described in his own words: [2] —

> In ground plan the canyon heads crowded upon the summit upland, frequently intersecting. They scalloped its borders, producing remnantal table effects. In plan as in profile, the inset arcs of the amphitheatres were vigorously suggestive of basal sapping and recession. The summit upland — the preglacial upland beyond a doubt — was recognizable only in patches, long and narrow and irregular in plan, detached and variously disposed as to orientation, but always in sharp tabular relief and always scalloped. I likened it then, and by way of illustration I can best do so now, to the irregular remnants of a sheet of dough on the biscuit board after the biscuit tin has done its work.

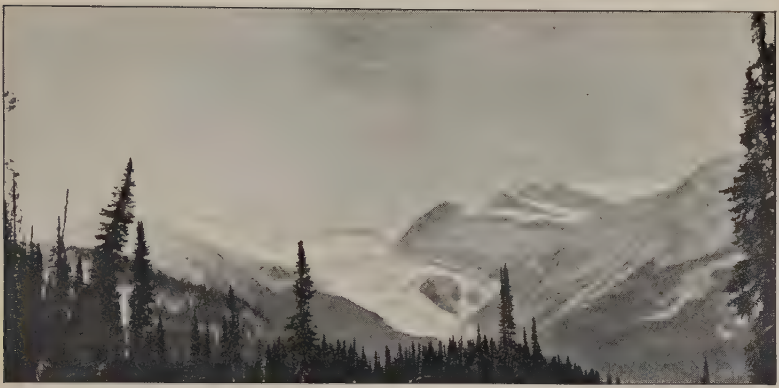
In a portion of the region where Johnson's studies were made, his views have received verification by Lawson in a beautifully illustrated paper.[3] Davis has furnished an excellent example from the Tian Shan mountains of the operation of the same cirque-cutting process, recording his adhesion to the Johnson doctrine,[4] though many of his later papers would indicate that he did not ascribe large importance to

the discovery.[5] In 1909 two papers from his pen give, however, larger prominence to the process.[6]

With little doubt the failure to generally recognize the importance of this process of cirque recession, clearly here a more effective agent than abrasion, is to be explained by the fact that in parts of Europe and in the Alps in particular, one looks in vain for evidences of the earlier and more significant stages of the process. Glaciation was here so vigorous as to cause the removal of all summit upland. Within the arid regions of the western United States, a more fruitful field for study is to be found. Here the work of Johnson has been supplemented by that of Gilbert[7] and Matthes.[8] Perhaps nowhere are the early stages of the process so clearly revealed as in the Bighorn Mountains of Wyoming (see Fig. 9).

FIG. 9. — Pre-glacial upland invaded by cirques — "biscuit-cutting" effect; Bighorn Mountains, Wyoming.

A somewhat more advanced stage of the same process is to be found in the Uinta mountains of Wyoming, recently described in a valuable monograph by Atwood, though here without consideration of the cirque-cutting process in accounting for the present topography.[9] Yet nowhere, so far as the present writer is aware, has a view been reproduced which so well illustrates the remnantal tableland and the "biscuit-cutting" process of cirque recession (see Fig. 10).[10] The present writer has photographed other examples of the



*A.* View of the Yoho Glacier at the head of the Yoho Valley, showing to the right a series of three small cliff glaciers. Canadian Rockies.

*B.* Pre-glacial upland on Quadrant Mountain, Y.N.P., invaded by the cirque known as the "Pocket."

same type in the Yellowstone National Park (see plate 3 B and Fig. 11). Remnants of the pre-glacial surface will, in

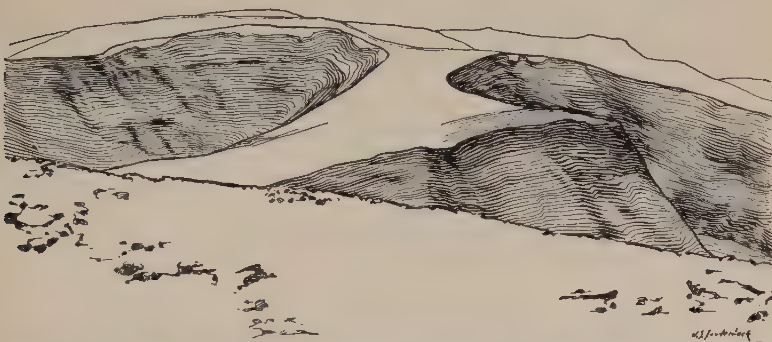


FIG. 10. — View of the scalloped tableland within the Uinta range and near the head of the west fork of Sheep Creek (after Atwood).

any given district, be large or small according as nourishment of the glaciers has been insufficient or the reverse. The Uinta range, which extends in an east-west direction, and,


FIG. 11. — Map of Quadrant Mountain, a remnant of the pre-glacial upland on the flanks of the Gallatin Range, Y. N. P.

like the Bighorn mountains, has a core of homogeneous granitic rock, displays this fact. An examination of Atwood's map[11] shows that to the eastward, where the precipitation has been least, the remnants of the original upland are more considerable. This qualifying condition of glacier nourishment will be subject to some modification because of peculiarities in snow distribution. As shown by Gilbert, the

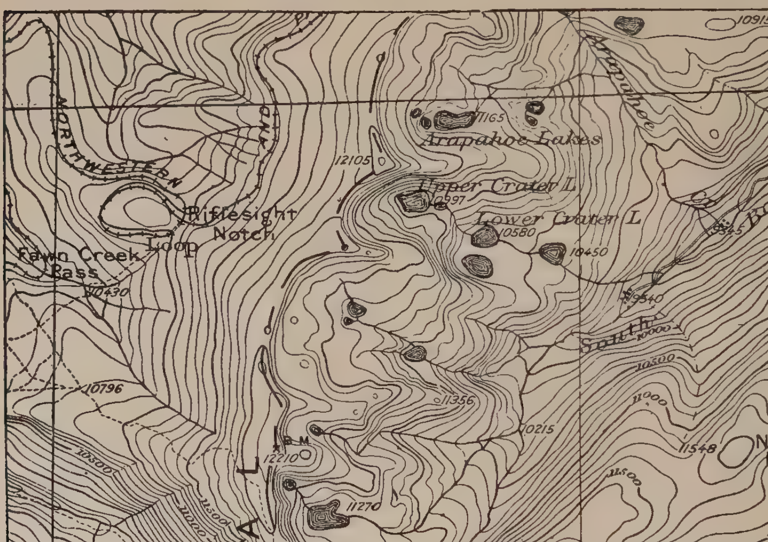
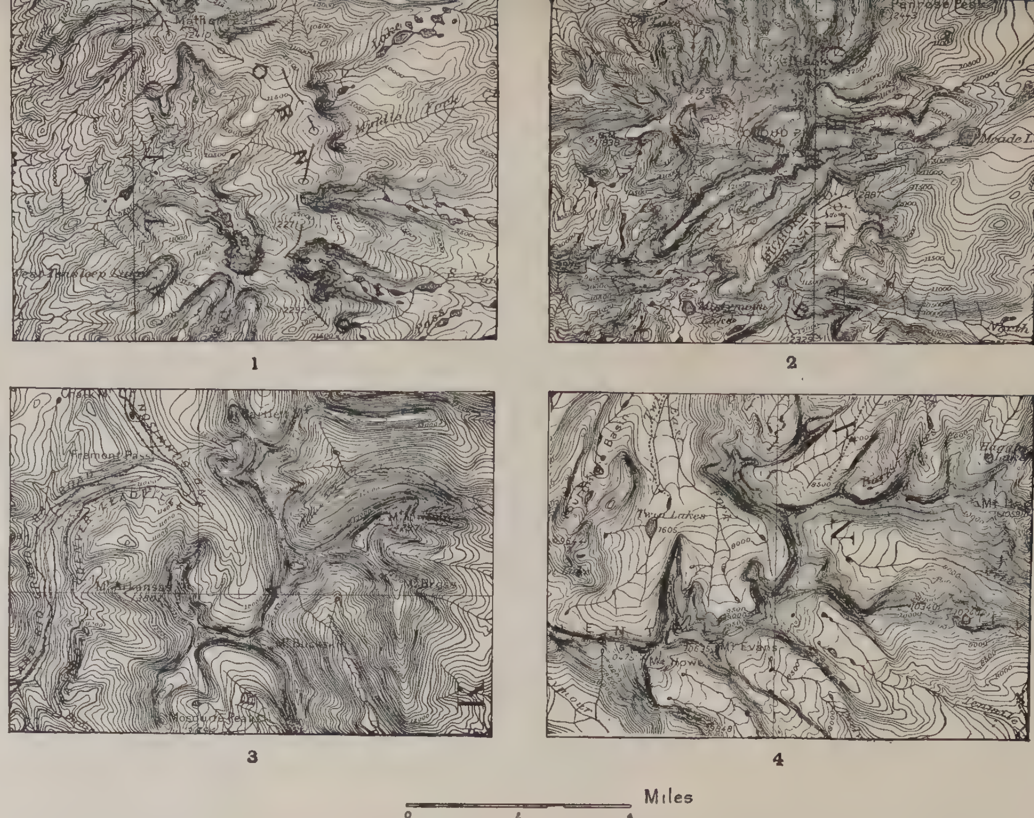



FIG. 12.—Series of semicircular glacial amphitheatres whose scalloped crest forms part of the divide of the North American continent.

first glaciers within any mountain district will probably appear upon that side of the divide which is in the lee of the prevailing winds. This fact is particularly well brought out in Fig. 12.

Such a condition as is here represented, gives a most decisive answer to the question concerning the protective or denuding action of glacier ice. To the west of the divide the snow has been swept clear, and these sweepings lodging in the lee have produced the glaciers on this side only.




SERIES OF FOUR MAPS TO ILLUSTRATE THE PROGRESSIVE DISSECTION OF AN UPLAND BY MOUNTAIN GLACIERS.

1. — Early stage of glaciation (Cloud Peak Quadrangle, Wyoming).
2. — Further investment of the upland, producing a *grooved upland* (Cloud Peak Quadrangle, Wyoming).
3. — Early maturity (Leadville Quadrangle, Colorado).
4. — Complete dissection at maturity, producing a *fretted upland* (Philipsburg Quadrangle, Montana).

Multiple secondary cirques on the west face of the Wannehorn seen across the Great Aletsch Glacier, to which it is tributary.

*(After a photograph by I. D. Scott.)*

While this glacial cover has no doubt protected its base from the ordinary weathering process, the extraordinary weathering in the Bergschrund combined with abrasion and plucking upon the floor, has excavated some 2000 feet of rock material, even if we were to assume that the " unprotected " surface to the westward has not been lowered.

The cwms of Wales have not as yet entirely removed the summit upland in which they have been recessed, and this residual surface perhaps furnishes the best European example of an earlier stage in the process of cirque recession.[12]

**Modification in the Plan of the Cirque as Maturity is Approached.** — Owing to the fact that the sapping process within the cirque operates on all sides, its early plan, when the upland surface is supplying snow from all directions, will approach the circle (see Fig. 9 and plate 3 B). Moreover, in this stage the cirque will be but little, if any, wider than the deepened and widened valley below (see plate 4, Figs. 1 and 2). Later, with the continuation of the sapping process, the cirque becomes enlarged to such an extent that its sides form recesses in the walls of the valley. Thus, in the plan, the glacial valley of this stage bears some resemblance to that of a nail with a large rounded head.

As the upland is still further dissected, the cirque becomes more irregular in outline and widens into a roughly elliptical form, not infrequently allowing it to be seen that it is in reality composite or made up of several cirques of a lower order of magnitude (plate 5, plate 6 B and Fig. 13).

**Grooved and Fretted Uplands.** — The new emphasis put upon topographic expression of character in the maps issued by government bureaus during the past few years, has furnished physiographers a tool of which they are hardly yet fully aware. Before, the aim of topographers seemed to be to suppress all character through a rounding off of angles and an averaging of the data. Perhaps nowhere has the change

been more noteworthy than in the maps issued by the United States Geological Survey,[13] and the later sheets particularly, when relating to glaciated mountain districts, afford us the opportunity of tracing the successive steps in the dissection of such upland districts by the cirques of mountain glaciers. For plate 4, four areas have been selected to represent successive stages in such a progressive dissection. An early product, in which large remnants of the upland surface still remain, may well be designated a "grooved or channelled" upland (see plate 6 A *a*).

As the hemicycle advances, it will be observed that on the flanks of the range are found the largest remnants of the original upland surface (see Fig. 11),[14] owing to the tendency of the cirque to push its side walls out beyond the limits of the U-shaped valley below. With complete dissection of the plateau no tabular remnants are to be discovered. The general level of the district has now been lowered, but above this irregular surface project one or more narrow pinnacled ridges — files of "gendarmes" — separated by crevices or "chimneys." These palisades at fairly regular intervals throw off lateral palisades having crests which fall away in altitude as they recede from the trunk ridge. In general terms, and describing the major features only, we have here to do with a gently domed surface, on which is a fretwork of comb-like ridges projecting above it. This surface may be designated a "fretted upland" (see plate 6 A *b*). Such a condition is realized in the Alps, and is seen to special advantage from the summit of Mont Blanc (see plate 7 A).

The transition from the grooved to the fretted upland is well brought out in two views taken by Lawson in the High Sierras of California (*loc. cit.*, plate 45, A and B). The fretted upland differs from the grooved upland of an earlier stage of the cycle in the complete dissection of the surface. The character of the fretted surface is well brought out by

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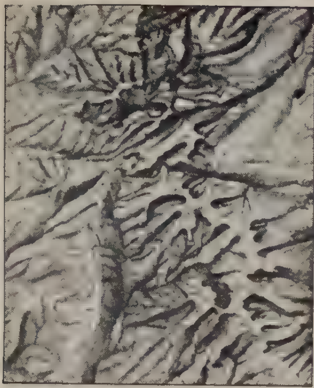
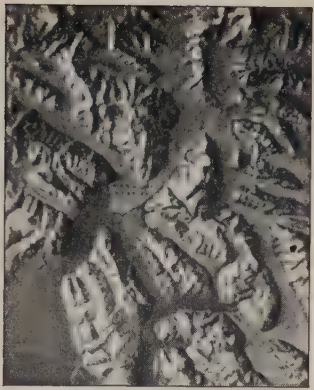
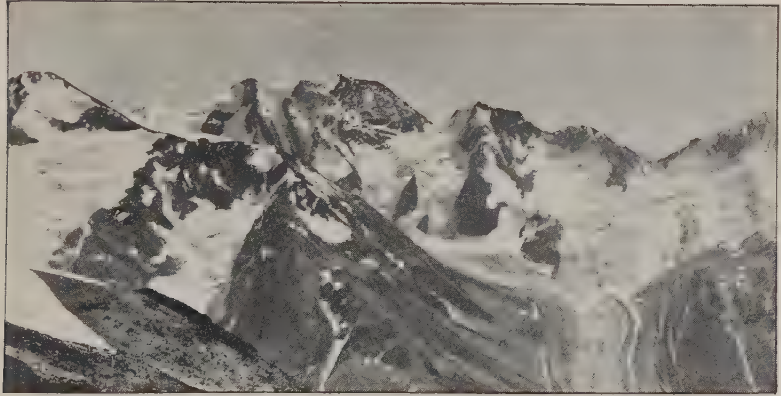


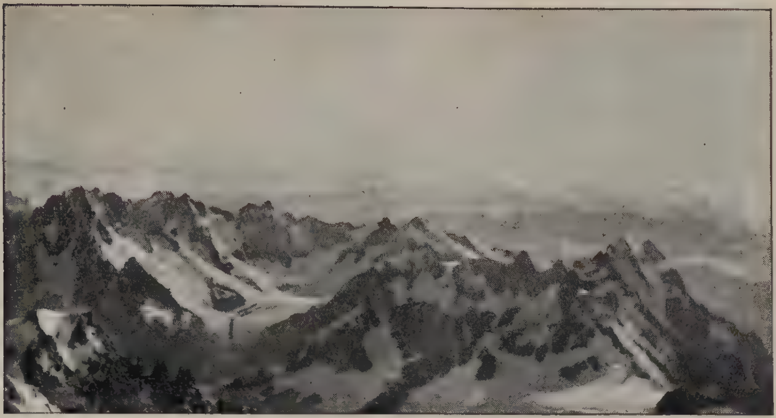
(b)



*A*. (*a*) A grooved upland in the Bighorn Mountains, Wyoming. (*b*) A fretted upland, Alaska.



*B*. Multiple cirque of the Dawson glacier, having a major subdivision into halves, which enclose, respectively, the Dawson and the Donkin névés. The view is from the Asulkan Pass, Selkirk Mountains.



*A*. Fretted upland of the Alps as seen looking northeastward from the summit of Mont Blanc, July 25, 1908. The cirque to the left is that of the Glacier de Talèfre, with the Jardin in its centre, and distant about 10 miles.


*B*. Map of a portion of one of the Lofoten Islands, showing a fretted surface partially submerged and emphasizing the approximate accordance of summit levels.

the topography of the Lofoten Islands off the arctic coast of Norway, where the effect is somewhat heightened through the partial submergence and consequent obliteration of the irregularities in the floor (see plate 7 B).

At this stage there is undoubtedly a general accordance of level in the crests of the frets upon the domed surface, as Daly, taking due account of the cirque-cutting process, has claimed.[15] Moreover, the existence of such a series of frets as are to be found in the Alps, forces us to conclude that such an accordance of summits persists for a considerable time. Were this not the case, we should find a larger number of low


FIG. 13.— Diagram to illustrate the manner of dissection of an upland by mountain glaciers.

cols and a longer persistence of the semicircular form of the cirque. It seems probable, therefore, that a very definite relationship obtains between the plan of the cirque and that of the near-lying upland remnants that contribute snow to its basin. So soon as cirques approach from opposite sides of a divide, the portions of their basins which are more nearly adjacent receive less snow, and, in consequence, accomplish less sapping than the walls on either side where snow is lodged in

a quantity but slightly diminished. This self-regulating process will tend to broaden the cirque and eventually give it irregularities of outline dependent primarily upon the initial positions and the individual nourishments of its near-lying neighbours.

**Characteristic higher Relief Forms of the Fretted Upland.** — In the earlier stages of mountain glaciation the upland is channelled by valleys U-shaped in their upper stretches, and somewhat broadened into steep-walled amphitheatres at their heads. With the complete dissection of the upland, the coalescence of the many cirques at last cuts away every remnant of the original surface and yields relief-forms which are dependent mainly, as already stated, upon the initial positions of the cirques.[16]

If there be a highest area within the upland, the snow will be carried farthest from it by the wind, and this will be in consequence the last to succumb to the cirque-cutting process. The dome of Mont Blanc in the midst of a forest of pinnacles, no doubt owes its peculiar form to the fact that it dominated the pre-glacial upland.

A high district whose area is not too large compared with that of the individual cirques, when at last dissected by the cirques may be designated a "karling."[17] A typical example from Northern Wales is represented in plate 8.

Elsewhere within the upland the coalescence of cirques has produced comb-like palisades of sharp rock-needles which have long constituted the *aiguille* type of mountain ridge. In the literature of physiography, such ridges have perhaps most frequently been designated by the term "arête" (fishbone), though in the Alps the term "grat"[18] (edge) has been applied especially to the smaller and lateral ridges of this type. I propose to use for all such palisades of needles derived by this process the name "comb-ridge"[19] as the best English term available. The frequent occurrence of lateral arms joined

PLATE 8.


A karling in North Wales (from the Bangor sheet of the British Ordnance Survey, 1907).

to the main palisade of needles suggests a differentiation into main and lateral comb-ridges.

In every mountain district maturely dissected by glaciers, are to be found sharp horns of larger base and especially of higher altitude than the individual minaret-like teeth of the comb-ridges. They are further in contrast with the latter by having an approximately pyramidal form, and a base most frequently a triangle with flatly incurving sides. They appear most frequently at the junction points of the comb-ridges between three or more important snow-fields (see Fig. 14). Such forms are generally termed "horns" in the Alps, and the word being of the same form in English, it may well be retained as a technical expression. The Matterhorn in Switzerland is the type *par excellence* (see plate 9 A), though similar and almost equally striking examples are numerous; as, for example, the Weisshorn and Gross Glockner in the Alps, Mount Assiniboine in the Canadian Rockies, or Mount Sir Donald in the Selkirks. The triangular base and pyramidal form are so common to this feature that they have found expression in the local names, as Dreieckhorn, Delta-form peak, etc.

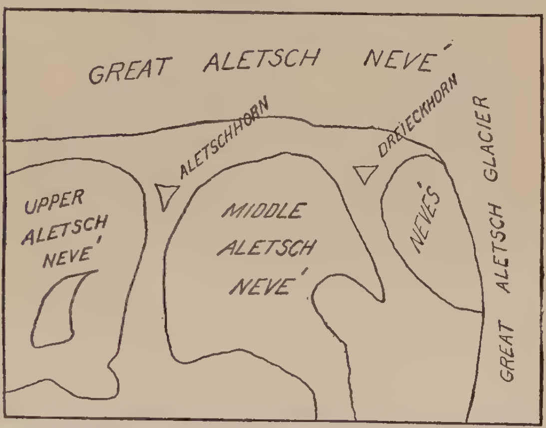



FIG. 14. — Position of the Aletsch- and Dreieckhorns between the Upper, Middle, and Great Aletsch névés.

**The Col and its Significance.** — The prominent horns of any glaciated mountain district no doubt occupy positions cor-

responding in the main to the more elevated areas in the original upland surface, since such positions would be earliest cleared of snow, and hence latest attacked by the cirques. After complete dissection of the upland, the comb-ridges which fret its surface will be attacked from opposite sides, and their crests will be first lowered at the points of tangency of the adjacent cirques — generally near the middle points of their curving outlines. The sky-line of the ridge will thus be lowered in a beautiful curve forming a pass or *col.* Inasmuch as the cirque approaches in its form an inverted and truncated cone of acuminated type, the curve to which the rim of the col approximates will be furnished by the intersection of two cones of revolution with the same apical angle and having parallel axes (see Fig. 15 and plate 9 B). This curve is approximately a hyperbola, the eccentricity of which will be largely dependent upon the relative sizes of the cirques in question.

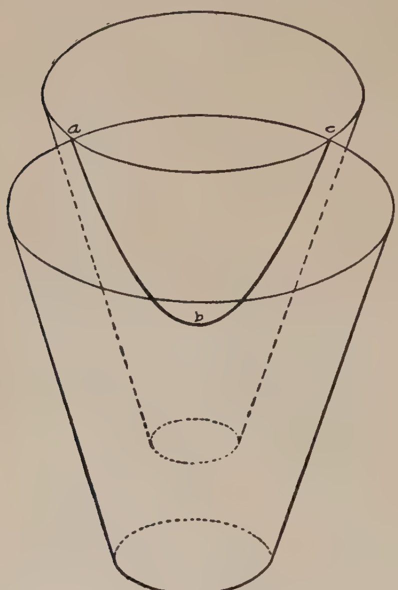


FIG. 15. — Diagram to illustrate the formation of a col through the intersection of cirques.

The corries of the Scottish Highlands, being generally of small size, have coalesced to produce a very characteristic scalloping of the horizon line seen to advantage in Ben Nevis, or, better still, in the sculptured gabbro of the Cuchulin hills in Skye.[20] To judge from views, also, such forms are found in North Wales, features which in many respects are different

*A.* View of the Matterhorn from the Gorner Grat.

(*After a photograph by I. D. Scott.*)

*B.* Col between Mt. Sir Donald and Yogo Peak in the Selkirks, showing the characteristic hyperbolic profile.

(*Copyright by the Keystone View Company.*)

from those found in the Alps or in the North American mountains.[21]

It must be regarded as of deep significance that mountain passes in areas which have supported glaciers are so generally at high levels. Deep glacier-cut valleys available as highways and transecting high ranges are extremely rare; so far as the writer is aware, being known only from the Southern Andes[22] and Alaska.[23] This fact must have its explanation, it is believed, in a notable and abrupt retardation in the rate of cirque-wall recession, following close upon the dissection of the upland. Whether this is due to the reduced snow accumulation immediately beneath the cirque wall owing to the lack of a near-lying collecting ground, it is as yet too early to say; but a comparison of the acclivities in the marginal snow-slopes on *névés* of the Bighorn and Alaskan districts might yield an answer to the question.

Though the sapping process at the base of cirque walls up to maturity is doubtless far more potent than abrasion and plucking upon the floor of the amphitheatre, it seems likely that in the subsequent stage the reverse is the case. This would at least explain the tendency of glacier valleys to deepen rapidly in the higher altitudes, or, in Johnson's phrase, to get "down at the heel."

**The Advancing Hemicycle.** — With the augmentation of rigorous climatic conditions within any district where glaciers already exist, the latter will be continually more amply nourished, and must in consequence increase steadily in size. Such climatic changes may even be conceived so considerable that at last the entire range is submerged beneath snow and ice, thus producing an ice-cap.

Direct observation of the successive stages through which glaciers pass from their initiation to their culmination in an ice-cap, is, of course, impossible, for the reason that we live in a receding hemicycle in which practically all known gla-

ciers, instead of expanding, are drawing in their margins; yet a synthetical reconstruction of the life-history is none the less possible. To employ an illustration already used in a different connection, in order to learn the life-history of a particular species of forest tree, it would not be necessary to sit down and observe an individual tree from the germination of its seed to the decadence of the full-grown tree. We may with equal profit go into the forest and observe trees of the same species in all stages of development. In the study of glaciers our opportunity is hardly so fortunate as this, for, as already stated, all glaciers appear to be in the declining stage (if we ignore the short period variations) whereas it is the advancing hemicycle with which we are now concerned. The characters of glaciers as concerns their size and shape depend, however, in so large a measure upon the one element of alimentation, that if we neglect characters of a second order of magnitude, we may by inference construct the history with sufficient accuracy from existing examples.

The alimentation of mountain glaciers is dependent upon the amount of precipitation and upon the temperature, the former being in large measure determined by the adaptability of the relief for local adiabatic[24] and contact refrigeration of the air. The important factor, temperature, while a function of many variables, yet in a broad way varies directly with latitude and altitude. The size and the form of glaciers is, however, determined, not solely by nourishment (mainly in the higher levels), but also to some extent by losses (particularly in the lower levels). In the main, however, the losses are controlled by the same factors as the gains, and maintain to them a more or less determinate proportional relationship. Exceptions to this definite proportion occur when in high latitudes the glacier is attacked directly by the sea (tidewater glaciers), when it is suddenly melted by the heat of a volcanic eruption (Icelandic Jökulls), or

when disturbed by a heavy earthquake (Muir glacier in 1899). In form glaciers will be in large measure determined by the existing topography of the upland, which may generally be assumed to be some product of sub-aërial erosion. Starting, therefore, with the puny glaciers of arid regions in low latitudes, and ending with the high latitude glaciers within areas of excessive precipitation, we run almost the whole gamut of glacier alimentation.

The initial forms of glaciers may be described as snow-bank, "new-born," or nivation glaciers, and will at first be few in number and located with wide intervening spaces of upland. The continuance of the nivation process will deepen other intermediate small depressions upon the upland, so that with increasing snowfall additional glaciers will appear in the spaces between the first as the latter are developing their amphitheatres. These cirques, at first no wider than the valleys below, will later cut recesses on either side, at the same time that the glacier is pushed farther down the valley and occupies its bed to a greater and greater depth. The grooved upland of this stage, through additional cirque recession in the highlands and through abrasion and plucking in the intermediate levels, becomes at last transformed into the fretted upland, with its network of projecting comb-ridges. Up to this point the glacier ice has, perhaps, been restrained within valleys, which it has discovered and has progressively widened and deepened. If the annual temperature continues to be lowered, there must come a time when the ice-feet from the better-nourished glaciers, or from those with the shortest route to the foreland fronting the range, will debouch upon the plain, spreading as they do so into fans or aprons (see plate 10 A). Later all neighboring glaciers may arrive at this stage, and by spreading upon the foreland, coalesce with one another to form a single broad apron, such as may be seen in the Malaspina glacier of Alaska

(see plate 10 B). While the glaciers are thus pushing out upon the foreland, they have been deepening in their valleys, and eventually come to overtop portions of the lateral comb-ridges of the fretted upland, thus moulding the sharpened needles into rounded shoulders of rock. In places the glaciers from adjacent valleys will flow together through the irregular depressions separating peaks, thus producing islands or *nunataks*.

But the increased size of the individual glaciers of the range has corresponded to increased activity of cirque recession in the high altitudes, and this has resulted in the formation of cols or passes through the range. Snow which has been divided at the summit, as has water by a divide, may now be consolidated into glacier ice over the col before the separation is made. Thus it comes about that without a definite cirque, glaciers will transect the range flowing in opposite directions from a central ice-field. Such a broad central ice-field is found to-day between Mount Newton of the St. Elias group and Mount Logan to the eastward.[25]

The advance of the glacier ice up the sides of the valleys, so as partially to submerge the lateral comb-ridges, may not end until all are thus covered and the ice flows away from the central broad area, radiating in many directions. Here the process of cirque recession, which has mainly sculptured the rock in the higher altitudes, comes to an end as we reach the ice-cap stage of glaciation. Transitions toward such ice-cap glaciers are to be found to-day in the Elbruz and in the Kasbek region of the Causasus, where a central elevated snow-field is the common *névé* of several glaciers radiating in as many directions.[26] It is of considerable interest to note that in the Caucasus district, at least, there is evidence that rocky comb-ridges are submerged beneath the ice and make their appearance so as to separate the marginal ice-tongues. The persistence of an ice-cap over

a mountain region, as is clear from study of the glaciated mountains in Eastern Lapland tends to largely obliterate relief forms characteristic of mountain glaciers as they are replaced by the rounded shoulders of "rundlings" or the smaller "roches moutonnées." As soon, however, as nourishment has been so far reduced that the higher points once more appear from beneath their snow cover, cirque recession will begin again, and, if long continued, the evidence of the ice-cap will disappear. Lack of glacial scratches or polish in uplands sapped by this process should, therefore, not be allowed to weigh too heavily in reconstructing the glacial history of a district.

## REFERENCES

[1] The term "upland" is here used in a general sense to designate any relatively elevated area of the land.

[2] W. D. Johnson, *Jour. Geol., loc. cit.*

[3] A. C. Lawson, "The Geomorphogeny of the Upper Kern Basin," *Bull. Dept. Geol. Univ. Calif.*, vol. **3**, No. 15, especially p. 357, pls. 32, 45.

[4] W. M. Davis, *Appalachia*, vol. **10**, 1904, pp. 279–280.

[5] *E.g.*, cf. *Scot. Geogr. Mag.*, vol. **22**, 1906, pp. 76–89.

[6] "Glacial Erosion in North Wales," *Quart. Jour. Geol. Soc.*, vol. **65**, 1909, pp. 281–350, pl. 14; also "The Systematic Description of Land Forms," *Geogr. Jour.*, vol. **34**, 1909, p. 109.

[7] *Jour. Geol., loc. cit.*

[8] *Ibid., loc. cit.*

[9] Wallace W. Atwood, "Glaciation of the Uinta and Wasatch Mountains," *Prof. Paper, U. S. Geol. Surv.*, No. 61, 1909, pp. 1–96, pls. 1–15.

[10] Other apt illustrations have been furnished by Lawson in a photograph taken in the Upper Kern region of the California Sierras (*loc. cit.*, pl. 32 B), and by Davis in a sketch made in the Tian Shan mountains (*Appalachia*, vol. **10**, 1904, p. 279).

[11] *Loc. cit.*, pl. iv.

[12] W. M. Davis, "Glacial Erosion in North Wales," *Quart. Jour. Geol. Soc.*, vol. **65**, 1909, figs. 7, 27, 28.

[13] See D. W. Johnson and F. E. Matthes, "The Relation of Geology to Topography." Reprint from Breed and Hosmer's "Principles and Practice of Surveying," chap. vii., Wiley & Co., N.Y., 1908.

[14] Other quadrangles of the U. S. Geological Survey which display the upland surface more or less completely dissected by mountain glaciers are the following: *early stage:* Younts peak (Wyoming), Marsh peak (Utah-Wyoming), and Georgetown (Colorado); *partial dissection:* Mount Lyell and Mount Whitney (California), Grand Teton (Wyoming), Gilbert peak

and Hayden peak (Utah-Wyoming), and Silverton and Anthracite (Colorado); *complete maturity:* Kintla Lakes (Montana).

[15] R. A. Daly, "The Accordance of Summit Levels among Alpine Mountains," *Jour. Geol.*, vol. **13**, 1905, pp. 117–120.

[16] The analogy with the forms produced by etching upon crystal faces is so striking that it may be helpful to note it in comparison. The first effect of a reagent in its attack upon the plane of a crystal face is the excavation of deep pits which have a similar and wholly characteristic form, though the surface in other places remains unchanged. These pittings later increase in number, as they do in size, and eventually they mutually coalesce, destroying utterly the original plane surface, and leaving in relief a series of hills and ridges (etch-hills) projecting above a somewhat irregular floor, whose average level is a measure of the average depth of the excavations made by the process. The noteworthy difference between this process and that of cirque recession in glaciated uplands is that the glacial etch-figures are relatively longer and narrower.

[17] Penck und Brückner, "Die Alpen im Eiszeitalter," vol. **1**, Leipzig, 1909, pp. 284, *et seq.*

[18] Very likely originally from *gräte*, fishbone.

[19] The use of *combe* in the Jura and the Cote d'Or for different types of valley, or of *coombe* in the Southern Uplands of Scotland for a glacial valley, being each essentially local and having further no relation to the toothed article which suggests the name comb-ridge, does not constitute a serious objection to this choice. Mr. Matthes (and possibly others) have already used the expression comb-ridge in the above described sense. (*Appalachia*, vol. **10**, 1904, p. 260).

[20] See Harker, "Glaciated Valley of the Cuchulins, Skye," *Geol. Mag.* (fig. 4), vol. **6**, 1899, p. 197; also "Ice Erosion in the Cuillin Hills, Skye," *Trans. Roy. Soc. Edinb.*, vol. **40**, 1901–1902, pp. 234–237.

[21] This characteristic form of cirque, partly open at the head, is well brought out in a view published by Sir Andrew Ramsey as early as 1852, *Quart. Jour. Geol. Soc.*, vol. **8**, p. 375.

[22] 'Argentine-Chilian Boundary in the Cordillera de los Andes.' 5 vols.

[23] R. S. Tarr, "Glaciers and Glaciation of Yakutat Bay, Alaska," *Bull. Am. Geogr. Soc.*, vol. **38**, 1906, p. 149.

[24] This term applied to change of temperature of a gas, implies that the change is due to change of pressure and volume and not to the communication of heat from outside. The heating of a bicycle tire on pumping or the cooling on emptying, may serve for illustration.

[25] Filippo di Filippi, "The Ascent of Mount St. Elias." Panorama at end of volume (unnumbered) from an elevation of 16,500 feet.

[26] H. Hess, "Die Gletscher," Braunschweig, 1904, pp. 65–68.

[27] Penck und Brückner, "Die Alpen im Eiszeitalter," vol. **1**, Leipzig, 1909, pp. 286–287.

# CHAPTER III

## CLASSIFICATION OF GLACIERS BASED UPON COMPARATIVE ALIMENTATION

**Relation of Glacier to its Bed.** — From what has been said in the preceding section concerning the changes of glaciers in correspondence with a progressive augmentation of glacial conditions, it must be evident that any attempt to use each circumscribed body of snow and ice as a unit in name or in type will lead to endless confusion. Ice bodies being extremely sensitive to changes in annual temperature, a difference of one degree may be sufficient to join many ice bodies into one, or to differentiate one body into many. If, however, we examine the distribution of snow and ice masses within the valley which they either wholly or partially occupy, it will be seen that there are relatively few distinct glacier types, and that the coalescence of smaller ice masses, or the breaking up of larger ones, does not necessarily alter the type exemplified.

The more important types called for by analysis on this basis do not differ greatly from those in general use; but the genetic relationships of these types are here first brought out, together with distinct and intermediate transitional forms. In the following table, excepting the initial type and the glaciers with inherited basins, the arrangement is in the main one of decreasing alimentation: —

**Nivation** type (Bighorn glaciers).
**Ice-cap** type (Jökulls of Iceland).
**Piedmont type** (Malaspina glacier).
**Transection** type (Yakutat glacier).
**Expanded-foot** type (Davidson glacier).
**Dendritic type**, normal sub-type (Baltoro glacier).
  Hanging glacierets (Triest glacier).
  Cliff glacierets (Lefroy cliff glacieret).
Dendritic type, Tide-water sub-type (Harriman-Fjord glacier).
Inherited basin type (Illecillewaet glacier).
  Reconstructed type (Victoria-Lefroy glacier).
  Volcanic cone type (Nisqually glacier).
  Cauldron type (Caldera glacier).
**Radiating** ("Alpine") type (Nicolaithal glacier).
**Horseshoe** type (Mount Lyell glacier).

**Nivation Type.** — This type of glacier has also been called "new-born" or "snowbank" glacier, and represents the initial stage of glaciation. Though small in size, such glaciers differ markedly from those of the same dimensions which cling to the steep walls of a large cirque (see horseshoe glaciers below), which Tarr has referred to as "dying glaciers."[1] Numerous examples of snowbank glaciers are furnished by the Bighorn mountains of Wyoming. Other known types of mountain glaciers are all represented, and follow naturally in sequence during a receding hemicycle of glaciation. In their discussion we shall conceive a mountain district to pass by slow stages from a culmination of glacial conditions toward a comparatively genial climate.

**Ice-cap Type.**[2] — Though in form and general characters resembling so-called continental glaciers, the ice-caps by reason of their smaller dimensions form a connecting-link with mountain glaciers, and are usually developed upon small plateaus or uplands. They correspond to conditions of extremely heavy snow precipitation, and in consequence

have not been found fully developed outside the polar or sub-polar regions (see inherited basin glaciers below).

The normal type of ice-cap glacier is represented by the mantle over Redcliff peninsula, north of Inglefield gulf in Greenland.[3] It suffers no interruption from mountain peaks, but the ice creeps out in all directions from a central area, and sends out marginal lobes and tongues which much resemble, save for their whiter surface, the snouts of dendritic and radiating glaciers (see below). The Jökulls of Iceland are very similar, and form flatly arched or undulatory domes of ice having short lobes about their margins (see plate 11, 1). The largest of these, the Vatnajökull, has an area of 8500 square kilometres.[4] In Scandinavia the smaller plateau glaciers with marginal tongues of proportionately greater length, such as the Jostedalsbiäen, serve to connect this type with that of the dendritic glaciers (see plate 11, 2).[5] The *Richtofeneis* on Kerguelen island, recently described by the German South-polar Expedition, seems to be very similar.[6] According to Meyer, the ice mass upon the summit of Kilimandjaro in Africa is an "ice carapace," having much resemblance to the ice plateaus of Scandinavia.[7]

**Piedmont Type.** — Piedmont glaciers, like ice-caps, correspond to conditions of exceptionally heavy precipitation, and are only known from sub-polar regions. In contrast to small ice-caps, the existing examples are found in connection with mountains of strong relief, so that the snow and ice which in ice-caps find their way slowly out to the margin of a flat or gently sloping plateau, are in the piedmont glacier discharged through valleys from lofty highlands to debouch upon the foreland at the foot of the range. The well-known type is the Malaspina glacier of Alaska, explored and described by Russell (see plates 10 B and 11, 3).[8] Near it and farther to the west is the Bering glacier of about the same size.[9] To the east of the Malaspina glacier is the Alsek, a

much smaller piedmont glacier.[10] In Chili south of 42° S. lat. are found other piedmont glaciers, among them the San Rafael.[11] During Pleistocene times piedmont glaciers existed in many mountain districts, notably, however, the Alps [12] and the Rocky mountains of North America.[13] An imperfect transition from the piedmont type toward the continental glacier is illustrated by the Friederickshaab glacier in Greenland, which pushes its front out upon the foreland as an extension of the inland ice of that continent (see Fig. 94, p. 171).

Above the ice-apron and within the range, the piedmont glacier bears a close resemblance to the dendritic type (see below), though in general it may be said that its valleys are filled to a much greater depth. The largest stream feeding the fan of the Malaspina glacier has been named the Seward glacier, while other tributaries are known as the Agassiz and the Tyndall (see plates 10 B and 11, 3). It is interesting to note that however steep these feeders to the ice-apron may be, the latter always shows an exceedingly flat slope, and is, moreover, relatively stagnant.

**Transection Type.** — In a late stage of augmenting glacial conditions or in an early stage of the receding hemicycle, what is essentially one body of ice may be divided over a pass and flow off in opposite directions toward different margins of the range. For this type, exemplified by the Nunatak glacier of Alaska, Tarr has used the term "through glacier,"[14] and Blackwelder has instanced the Yakutat glacier and perhaps the Beasley within the same region.[15] Such glaciers, which may be referred to as the *transection type*, are often the highways which give readiest access to the hinterland. A glacier of this type, which has been carefully mapped, is the Sheridan glacier near the mouth of the Copper river in Alaska (see Fig. 16).[16] An excellent panorama of one of the

*A.* Expanded fore-foot of the Foster glacier, Alaska.

*B.* Type of piedmont glacier.

*(From a photograph of the new model of the Malaspina glacier made under the direction of Lawrence Martin.)*

grandest transection glaciers has been furnished by Sella.[17] The glaciation of the Grimsel pass in Switzerland clearly indicates that at one time a glacier of this type was parted over the present divide, one stream passing down the Rhone

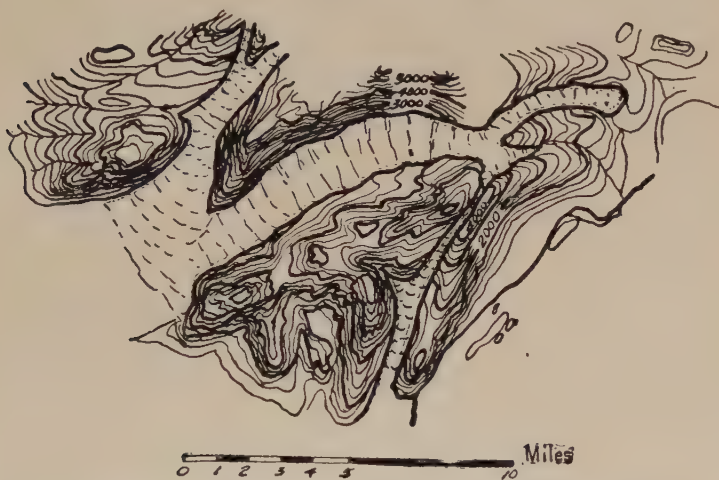



Fig. 16. — Map of a transection glacier, the Sheridan Glacier near the Copper River in Alaska (after G. C. Martin).

valley, and the other down the Häsli valley toward Meiringen. Far grander exhibits of the same sort are to be found in the Southern Andes.[18]

**Expanded-foot Type.** — When a piedmont glacier draws in its margin as it shrinks with the coming of a warmer climate, the several ice-streams which feed the apron of ice upon the foreland end in smaller fans at the mouths of the individual valleys. Perhaps the best known example of such an expanded-foot glacier is the Davidson, on the Lynn canal in Alaska, though the Foster and Mendenhall glaciers of the same district are similar (see plate 10 A). The Miles and Childs glaciers, near the Copper River, are also of this type, and have been mapped by Martin.[19] The transection glacier known as the Sheridan is in the same vicinity, and has

an expanded forefoot — a good illustration of the combination of these two types in one (see Fig. 16). The type *par excellence* of the expanded-foot glacier is the Baird glacier on the Copper River (see Fig. 17).[20] A larger but less perfect example of the expanded forefoot than any thus far mentioned is the Klutlan, in the Yukon basin, whose foot extends a number of miles beyond the front of the St. Elias


FIG. 17. — The Baird glacier, a typical expanded-foot glacier (after Tarr and Martin).

range.[21] The Martin river glacier in the Copper river district affords another example, since it expands for a distance of over 20 miles. It is, however, partially restrained by a range of hills rising on its southern margin, and by Martin has been considered intermediate between the piedmont and valley types.[22]

**Dendritic or Valley Type.** — Retiring within the range as warmer temperatures succeed to more rigorous conditions, glaciers are of necessity restricted to individual valleys and their tributaries. They come thus to have a plan as truly arborescent as that of water-drainage, and they may in this stage be called "dendritic glaciers." Unfortunately, the term "valley glaciers," in every way appropriate, has been generally applied to glaciers which occupy valley heads only, and hence the term would have to be redefined in its natural rather than its inherited significance. This glacier type geographers are most familiar with in restorations of Pleis-


Fig. 18. — Outline map of the Hispar glacier, Karakorum Himalayas (after Conway).

tocene glaciers,[23] but it is none the less a common form to-day in districts more distant from commercial centres, and hence less easily accessible for study. From the Karakoram Himalayas, the Baltoro, Hispar, and Biafo glaciers, all of this type, have been described and carefully mapped by Sir Martin Conway.[24] An outline map of the Baltoro glacier is reproduced in plate 11, 4 and one of the Hispar glacier in Fig. 18. Other valley glaciers, generally less extensive,

have been mapped by Garwood[25] from the Kangchenjunga Himalayas. In the Central Tian Shan mountains are other glaciers of this type.[26] In the New Zealand Alps the Tasman glacier furnishes another example of the same valley type[27] (see Fig. 19 and plate 11, 5). Still other examples have

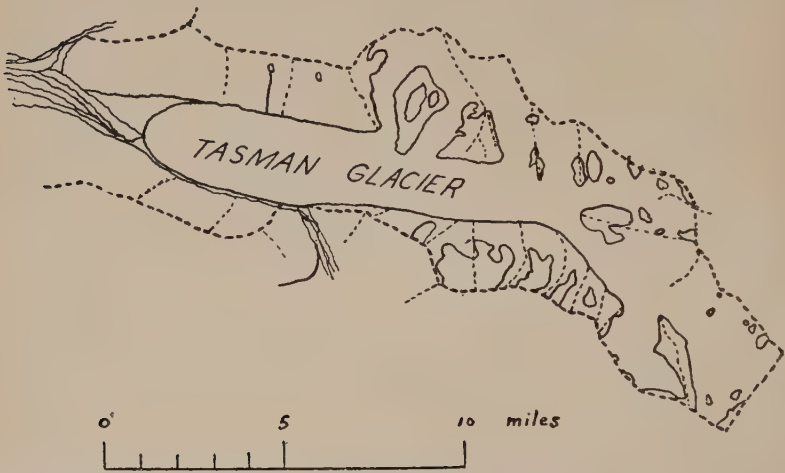



FIG. 19. — Outline map of the Tasman Glacier, New Zealand (after v. Lendenfeld).

been described from the mountains of Alaska, such, for example, as the Kennicott and Chistochina glaciers.[28]

Comparison of a number of examples of valley glaciers may illustrate as many different stages in the retreat of the glacier from a position in which it occupied its entire valley, to the retirement almost within the mother cirque at the head. The examination of the vacated valley has taught us that the tributary glaciers erode their beds less deeply than the trunk stream lying in the main valley. It is the surfaces of the ice-streams only that are accordant, and hence a lack of accordance in the bed levels has yielded the so-called hanging valleys with their characteristic ribbon falls. Nowhere can the hanging valleys be observed in greater perfec-


TYPES OF MOUNTAIN GLACIERS.

1–2, ice-cap types from Iceland and Norway respectively; 3, piedmont type, Alaska; 4–5, dendritic types from the Himalayas and New Zealand respectively; 6, dendritic type (tidewater glacier), Alaska; 7–8, radiating types, Alps; 9, radiating type, Himalayas; 10–12, horseshoe types from Himalayas, Selkirks, and Canadian Rockies respectively; 13, horseshoe type, Colorado; 14–15, inherited basin types from Alps and Selkirks respectively; 16, inherited basin type (reconstructed glacier), Canadian Rockies.

tion or on a grander scale than in the troughs, now largely abandoned of ice, which enter the great fjords of the "inside passage" to Alaska (see plate 13 A).[29]

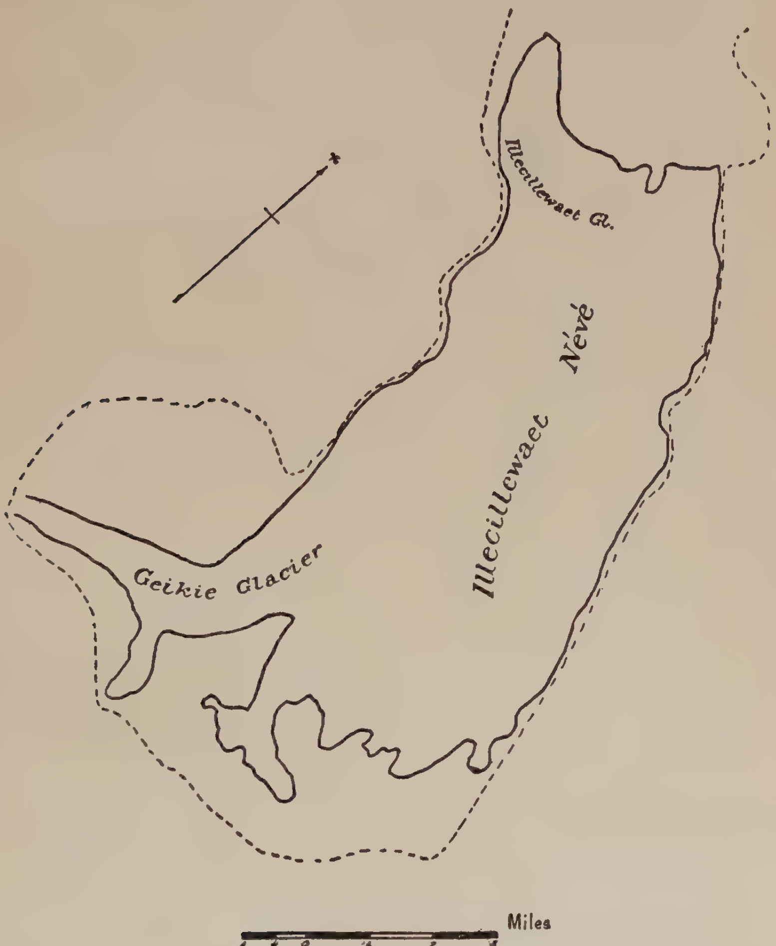



FIG. 20. — Outline map of an inherited basin glacier, the Illecillewaet Glacier of the Selkirks. The dotted line is the divide (after Wheeler).

As the foot of the trunk glacier retires up its valley, the lateral tributaries which are nearest the mouth of the valley

are at first separated from it and develop their own front moraines. Later they are left high above the main stream as a series of "hanging glacierets" (see plate 12).[30] The series of hanging glacierets, as will be observed in the maps of the Baltoro and Hispar glaciers, often persist above the main valley well below the foot of the trunk stream.

**Inherited Basin Type.** — The dendritic type of glacier hardly appears in the Alps at all, though the Great Aletsch glacier might, perhaps, be regarded as a small and imperfect example. The size and characters of the latter are, however, for the district in which it lies, abnormal and to be accounted for by the existence of a natural interior trough lying between the Berner Oberland on the one side and the high range north of the Rhone valley upon the other, from which basin small outlets only are found through the southern barrier (plate 11, 14). A better example, however, of this special type of glacier, in which the inherited topography has exercised a greater influence upon the glacier form than has the auto-sculpture, is furnished by the Illecillewaet glacier of the Selkirks (see Fig. 20), which, from a roughly rectangular snow-ice field lying between parallel ridges, sends out short tongues leading in different directions. A glacier of this type, with a moderate increase only of alimentation, would produce a small ice-cap.

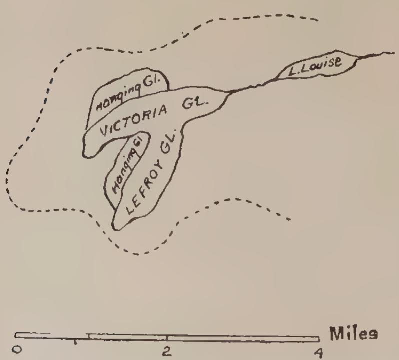



Fig. 21. — Outline map of a reconstructed glacier, the Victoria and Lefroy glaciers in the Selkirks (after Wheeler).

Another abnormal form of glacier due to the peculiarities of the basin which it inherited, is illustrated by the Victoria glacier in the Canadian Rockies, a glacier

A hanging glacieret, the Triest glacier, above the lower stretch of the great Aletsch Glacier, Switzerland.

(*After a photograph by I. D. Scott.*)

having no cirque, but only a couloir (the so-called "death-trap") in its stead (see Fig. 21). In this case the *névé* which feeds the glacier is found high above upon the cliff — a true cliff glacieret — and this *névé* avalanches its compacted snow upon the surface of the Victoria glacier, which thus well illustrates the *reconstructed type*.[31]

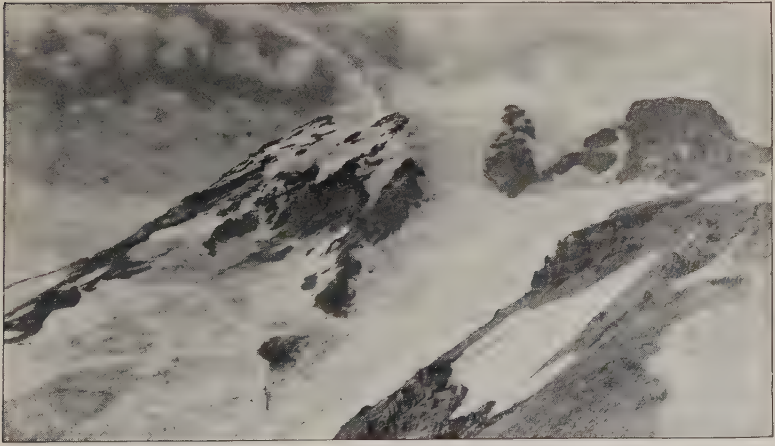
Again, glaciers may develop, not upon a gently domed and variously moulded pre-glacial upland such as we have thus far had under consideration, but upon the sharply conical volcanic peaks which in temperate and tropical regions push their heads from the mountain upland at their base far up above the snow-line. In such cases, regular cirques cannot develop at the heads of the radiating ice-streams, but, on the contrary, very irregular and mutually destructive forms will result (see plate 13 B).[32] This is the more true because of the loosely consolidated tuffs of which such cones are always built up. If sufficiently lofty, the result may be a small carapace or ice-cap such as is found to-day upon the summit of Kilimandjaro in Africa. On the other hand, a partially ruined crater may furnish a natural basin or cauldron for a small glacier — *cauldron type*.[33]

**Tide-water Type.** — In high latitudes glaciers sometimes descend to the level of the tide-water in fjords which continue their valleys. In such cases, the glacier front is attacked mechanically by the waves and is further melted in the water. In place of the convexly rounded nose, so characteristic of the other types, there develops a precipitous cliff of ice from which bergs are calved, and the glacier front in consequence is rapidly retired (plate 11, 6). Unhappily, the local term "living glaciers" has been applied to this type in Alaska; "dead glaciers," in the same usage, being applied to glaciers which yield no icebergs. The slopes of the glacier surface and the measure of projection of the ice above the water-level both render it probable that in most

cases, at least, the ice-foot everywhere rests on a solid basement. On the other hand, the Turner glacier, debouching into Disenchantment Bay, Alaska, shows a flat and relatively low front section, which is separated from the remaining and sloping portion of the glacier by a steep ice-fall. This has led Gilbert to think that the lowest terrace is floated in the water.[34]

**Radiating (Alpine) Type.** — A good deal of misunderstanding is current in regard to alpine glaciers, often unhappily referred to as valley glaciers. Examination of any good map of Switzerland suffices to show that with the possible exception of the Great Aletsch, an abnormal type, Swiss glaciers hardly extend into valleys at all. We have too long held the alpine glacier close before the eye, and so have much exaggerated its importance. When Alaskan, Himalayan, and New Zealand glaciers are brought into consideration, the real position of the Swiss type becomes apparent. In reality the glaciers of the Alps, far from occupying valleys, do not even fill the mother cirques at the valley heads. Here they lie, side by side, joined to one another like the radiating sticks within a lady's fan, for which reason they have sometimes been called *Zusammengesetzte Gletscher* (see Fig. 22 and plate 11, 7). The *mer de glace*, next to the Great Aletsch the largest in Switzerland, with its numerous tributaries, it is true, completely fills a cirque, but only that of a tributary valley (plate 11, 8).[35] Alpine glaciers are hence sheaves of small glaciers or glacierets which start out from the secondary scallops of the mature cirque. They are wholly included within the mother cirques, or fill and extend out from the secondary or tributary cirques. In the Nicolai valley of Switzerland, the Gorner glacier and its several tributaries (see Fig. 22), with the Findelen and Längenfluh, the Theodul, Furgen, and Z'Mütt glaciers together, but partially fill the mother cirque of which Zermatt is the centre. Lining

*A.* A hanging tributary valley meeting a trunk glacier valley above the present water-level on the "inside passage" to Alaska.



*B.* Irregularly bounded névés upon the volcanic cone of Mt. Ranier.

the valley below upon either side are eighteen to twenty glacierets, all resting upon the *albs*, or high mountain meadows.

High up in the Chamonix valley, below the debouchure of the *mer de glace*, similar glacierets are lodged upon the ledge

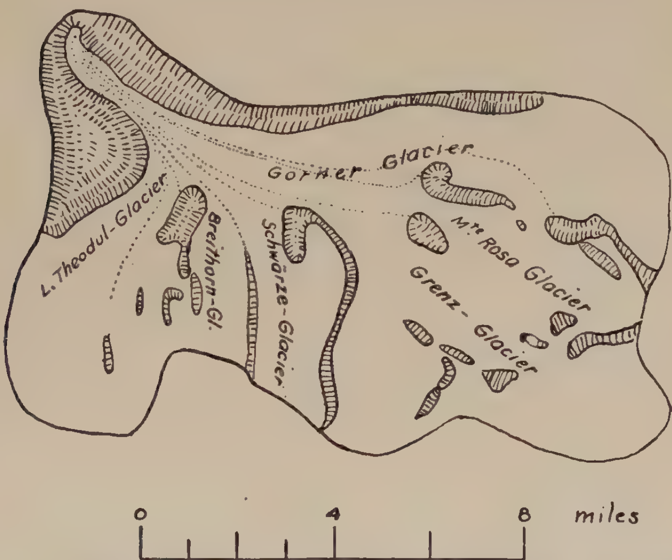



FIG. 22. — Outline map of a radiating glacier, in the Nicolai valley, Switzerland.

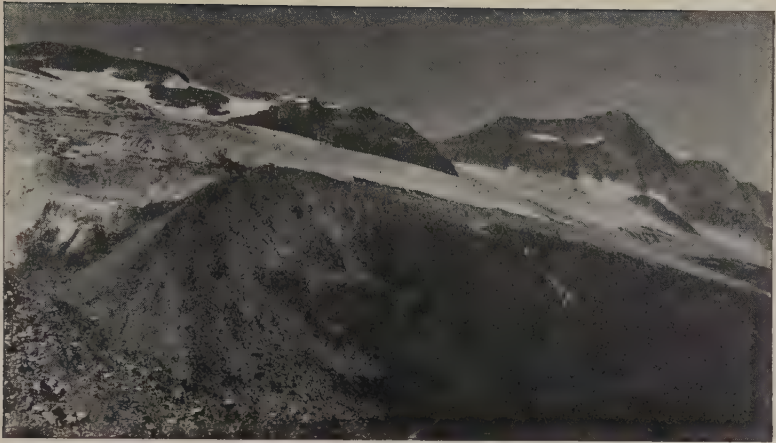
below the sharp needles of de Charmoz, de Blatière, du Plan, and du Midi, their frontal moraines making a continuous series of scallops above the shoulder of the valley. Similar but smaller series are shown in Fig. 23 and pl. 14 A.

**Horseshoe Type.** — The final representative type in our series, unlike the alpine glacier, is no longer made up of ice-streams joined together in sheaves. With further shrinking of alpine glaciers corresponding to higher air temperatures, the glacier front retires until it approaches the cirque wall. It now takes on, either as an individual or as a collection of small remnants, a broadly concave margin, which is in con-

trast to the convex or convexly scalloped front characteristic of all other glacier types. This type of glacieret has been sometimes described under the names "hanging" and "cliff glaciers."[36] Reasons have been presented for restricting both these terms to special and different varieties of small glaciers or glacierets. It is proposed to use here the term "horseshoe glacier" for these last remnants of larger glaciers


Fig. 23. — Outline map of a horseshoe glacier, the Asulkan glacier in the Selkirks. The dashed line is the divide.

hugging the wall of the cirque. Most of the glaciers of North America outside of Alaska belong in this class. As already implied, they are generally broader than long, and usually have concave frontal margins. Excellent examples of this type are furnished by the Horseshoe glacier at the head of the Paradise valley in the Canadian Rockies and by the Asulkan glacier in the Selkirks (see Fig. 23 and plate 14 A). The Mount Lyell glacier, long known and cited



*A*. Series of hanging glacierets which extend the Asulkan glacier in the Selkirks.

*B*. View of the Wenkchemna glacier at the head of the valley of the Ten Peaks in the Canadian Rockies.

from the High Sierras of California, is, however, an equally good type.[37] For further illustration of the type the Wenkchemna glacier in the Canadian Rockies has been chosen (see Fig. 23, plates 11, 2 and 14 B). The Asulkan and Wenkchemna glaciers have both been described by Scherzer as belonging to the piedmont type. The former hugs a cirque wall with an incurving frontal margin, and is extended by a series of small hanging glacierets (see plate 14 A). Unlike the piedmont glaciers, it has no foreland on which to expand, but lies in a cirque at the head of a typical U-shaped valley. The Wenkchemna glacier occupies a similar position in the great cirque outlined by the Ten Peaks at the head of a valley tributary to the Bow (see Fig. 24).[38]

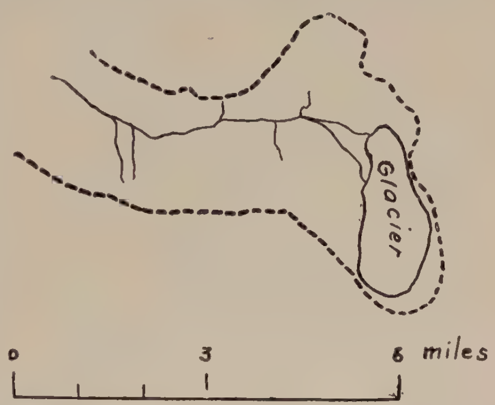



Fig. 24. — Outline map of the Wenkchemna glacier in the Canadian Rockies. The dashed line is the divide.

In plate 11 the various types of glacier are shown on approximately the same scale, and from this it will be appreciated that the size, directly dependent upon the alimentation of the glacier, must be a determining factor in classification. The ice-cap and piedmont glaciers will in this respect overlap, being differentiated by the accentuation of the relief of the land. For the other types the proportion of the glacier-carved valley which is still occupied by the ice will determine the form and the more important characters of the existing glacier. It is important, therefore, in order to determine the type to which an individual glacier belongs,

to map the divide surrounding the valley, as well as the boundaries of the glacier which lies within it. It will be shown later that in Antarctica, where melting of snow or ice occurs only under exceptional and local conditions some additional glacier types are encountered (see chapter xv).

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[4] Th. Thoroddsen, "Island, Grundriss der Geographie und Geologie, V. Die Gletscher Islands," *Pet. Mitt.*, Erg. Bd. **32** (Nos. 152–153), 1906, pp. 163–208, map, pl. xii.

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[6] Emil Werth, "Aufbau und Gestaltung von Kergulen." Sonderabd. aus Deutsch. Südpolar Expeditionen, 1901–1903, vol. **2**, pp. 93–183, pls. 9–14, 3 maps.

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[12] Penck u. Brückner, 'Die Alpen im Eiszeitalter,' especially vol. **2**, 1909, map opposite p. 396.

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[16] G. C. Martin, *Bull. 284, U. S. Geol. Surv.*, 1906, pl. 12.

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[19] G. C. Martin, *loc. cit.*

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[23] One of the best maps of such a restored valley glacier of Pleistocene age is that of the Kern valley of California (see Lawson, *loc. cit.*, pl. xxxi.).

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[25] E. J. Garwood, "Notes on Map of the Glaciers of Kangchenjunga, with remarks on some of the Physical Features of the District," *Geogr. Jour.*, vol. **20**, 1902, pp. 13–24, plate.

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[27] R. v. Lendenfeld, "Der Tasman Gletscher und seine Umrandung," *Pet. Mitt.*, Erg. Bd., vol. **16**, 1884, pp. 1–80, map, pl. 1.

[28] W. C. Mendenhall and F. C. Schrader, "The Mineral Resources of the Mount Wrangell District, Alaska," *Prof. Pap. U. S. Geol. Surv., No. 15.* 1903, pl. iv and ix. See also Brooks, *Prof. Pap. U. S. Geol. Surv., No. 45*, map, pl. xxxiv.

[29] R. S. Tarr, "Glacier Erosion in the Scottish Highlands," *Scot. Geogr. Mag.*, vol. **24**, 1908, pp. 575–587.

[30] The term "hanging glacier," now used in a variety of senses, is, it is believed, best retained with the restricted meaning. The term "cliff glacier," generally considered synonymous, may be restricted to the long strips of incipient glacier ice which sometimes parallel the main valleys on narrow terraces above precipitous cliffs which are primarily determined by the rock structure (see *ante*, p. 54; and also Matthes, *Appalachia*, vol. **10**, 1904, p. 262). In the sense here employed, a hanging glacier is generally the equivalent of the *Kahrgletscher*, a term quite generally employed in Germany. The term "horseshoe glacier" we have here suggested for an essentially different type of glacieret (see p. 53).

[31] See map and description of this glacier by Scherzer, "Glaciers of the Canadian Rockies and Selkirks," *Smith. Contrib.*, No. 1692, 1907, chaps. 2–3.

[32] Cf. I. C. Russell, "Glaciers of Mount Ranier," *18th Ann. Rept. U. S. Geol. Surv.*, 1898, pp. 329–423.

[33] Hans Meyer, "Der Calderagletscher des Cerro Altar in Equador," *Zeitsch. f. Gletscherk.*, vol. **1**, 1906–1907, pp. 139–148.

[34] G. K. Gilbert, 'Harriman Alaska Expedition,' vol. 3, "Glaciers," 1904, pp. 67–68. See also Tarr and Butler, "The Yakatat Bay Region, Alaska, Physiography and Glacial Geology." *Prof. Paper No. 64, U. S. Geol. Surv.*, 1909, pp. 39, 40, pl. *xa*.

[35] This valley is a large hanging valley tributary to the Chamonix valley, which latter alone is comparable in size to those that form the beds of the Baltoro, Hispar, and Tasman glaciers. If at first it seems that confusion may result from the introduction of valleys of different orders of magnitude, a second thought suffices to show that the difficulty is of theoretical rather than of practical importance, at least so far as existing examples of glaciers are concerned.

[36] See footnote on p. 57.

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[38] Sherzer, *Smith. Contrib.*, No. 1693, 1907, chaps. iv. and vii. The only resemblance to the piedmont glacier is in the shape. Neither glacier expands upon a foreland, but both lie in cirques at the heads of U-shaped valleys. They have no appreciable tributaries, and, as already pointed out, piedmont glaciers are necessarily of large size, corresponding to excessive precipitation.

# CHAPTER IV

## LOW LEVEL GLACIAL SCULPTURE IN MODERATE LATITUDES

**The Cascade Stairway.** — No one who has climbed a mountain glacier to its *névé* has failed to be struck by the alternation of plateau and precipitous slope, for the surfaces of mountain glaciers are, with few exceptions, broken into broad terraces. Each steep descent is well understood to overlie a corresponding fall in the glacier-bed. Perched upon the high cliffs which overlook the Pinnacle pass during his first attack upon Mount St. Elias, the late Professor Russell wrote of these terraces:[1] —

Were the snow removed and the rock beneath exposed, we should find terraces separated by scarps sweeping across the bed of the glacier from side to side. Similar terraces occur in glaciated canyons in the Rocky Mountains and the Sierra Nevadas, but their origin has never been explained. The glacier is here at work sculpturing similar forms, but still it is impossible to understand how the process is initiated.

The generalized description of uncovered glacier-beds within the High Sierras of California — perhaps as well as any that has been penned — lays the emphasis upon the more essential and impressive characters:[2] —

"The amphitheatre bottom terminated forward in either a cross cliff or a cascade stairway, descending, between high walls, to yet another flat. In this manner, in steps from flat to flat, common

enough to be characteristic, the canyon made descent (see Fig. 25 and plate 15). In height, however, the initial cross cliff at the head dominated all. The tread of the steps in the long stairway, as far as the eye could follow, greatly lengthened in down-canyon order.

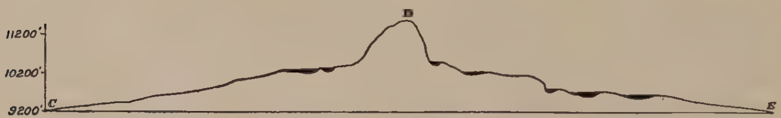


Fig. 25. — Longitudinal section along a glaciated mountain valley, showing reversed grades and rock basin lakes in series. Vertical scale about two and one half times the horizontal (after Salisbury and Atwood[3]).

The grade on the treads is often reversed, so that rock ridges separate basins or colks, and these latter come to be occupied by the characteristic glacial lakes. High up in the valley, where the treads are relatively short, these lakes are more or less kettle-shaped, though relatively shallow, and they usually rest directly upon the rock. They are, therefore, often referred to as *rock basin lakes*, though a morainal dam sometimes plays a part in impounding the water (Fig. 44, p. 82). Often connected together like pearls upon a thread, or, better still, like the larger beads in a rosary, they are sometimes referred to as *pater noster lakes* [4] (see Fig. 12, p. 28). Lower down in the valley and upon the longer treads, lakes are more apt to be long and ribbonlike in form (see plate 15).

**Mechanics of the Process which produces the Cascade Stairway.** — Since Russell's meditation above the Pinnacle pass, nearly a score of years ago, considerable study has been given to the subject of erosion upon the glacier-bed. In the Alps, Penck and Brückner have enunciated their "law of adjusted cross-sections." The glacier, on invading the mature river-valley, characterized by uniformly forward grades and by accordance of trunk with side valleys, will, in general, be so modified that a small cross-section corresponds to a deepening of the valley.[5] Thus may be brought


Land surface moulded by mountain glaciers near the ancient Lake Mono, east of the Sierra Nevadas in California (after Russell).

about the hanging side valley, and a local modification of, and perhaps even a reversal of, direction in the grade of the main valley.

If the rock be not homogeneous throughout, or if it be unequally intersected by joint planes, further abrupt changes in grade will result. The two processes which are effective in deepening the bed of the valley are well recognized to be abrasion and plucking. Greater softness in the rock will correspond to greater depth of abrasion, while the perfection of the parting planes will directly determine the amount of quarrying in the rock by plucking. Abrasion being greatest on the upstream side of any irregularity in the bed, and plucking being largely restricted to the downstream side, the tendency of these processes working together will be to produce steps of flat tread but steep riser, the latter coinciding with the nearly perpendicular planes of jointing. To quote de Martonne,[6] "the mass of the ice does not rest everywhere upon its bed, and in particular upon the risers of steps (Mer de Glace, Fiesch, Rhone glacier). Speaking generally, the contact becomes closer with each diminution of the down slope; it tends to be relaxed with each increase of the slope."

It is further probable that the cliffs at the lower margins of the terraces are in many cases, at least, considerably recessed through the operation of a sapping process in every way analogous to that which obtains at the base of the Bergschrund, or *Randspalte*. So soon as the rock cliff has been formed, either below a narrowing of the valley or where a hard layer of rock transects it, the glacier will descend over it in an ice-fall, showing gaping transverse crevasses. These fissures in the ice may be sufficiently profound to admit the warm air at midday to the rock joints, and so bring about with the nightly fall of temperature a mechanical rendering of the rock.

Basal cliff sapping being downward as well as backward, the reversed grades of the treads in the staircase could be thus explained. In the Alps, Penck distinguishes especially one larger cliff in the staircase which separates the head cirque from the trough valley (*Trogthal*).[7]

The extended studies of Penck and Brückner upon the Alps have shown that as a general rule the risers of the steps are found just above the junction of the main valley with

FIG. 26. — Rock bar with basin showing above, from the Upper Stubaithal near the Dresdner Hütte (after Brückner).

its tributaries.[8] Thus the main glacier stream is here reinforced by large contributions of ice and accomplishes a larger amount of excavating upon its bed. Sausage-like the valleys widen below the steps so that deeper basins

alternate with higher narrows and afford a certain correspondence between the plan and the profile of the valley.

Owing to the backward tilt of the treads within this cascade stairway, their outer edges rise from the sanded and in part flooded floor in the form of a rocky bar which crosses the valley from side to side. These bars are the well-known *Riegel*[9] or *verrous*[10] of the Swiss Alps, which for want of a better English designation we may term "rock bars." The topographic form of such bars is well brought out in Fig. 26. In many Alpine valleys such bars are quite numerous, no less than eight being encountered in a walk down the Häslithal from the Grimsel to Meiringen. The largest and best known of these is the famous *Aarschlucht* near Meiringen. Many of the larger Riegel are found to correspond in position to the outcropping of a zone of limestone, which, being less easily eroded by the glaciers than is the surrounding gneiss rock, has in consequence been left in relief.[11]

**The U-Shaped Glacier Valley.** — To-day it is everywhere recognized that one effect of the occupation of valleys by mountain glaciers is to so transform them that the cross-section has the form of a letter U. The steepness and the height of the side walls will, in hard rocks at least, be to some extent a function of the depth to which the valleys have been filled by the glaciers. Thus the Little Cottonwood canyon on the western front of the Wasatch range, so often cited and figured as a typical U-valley (see plate 16 A), is one in which the ice-foot pushed out but a short distance beyond the portal of the valley. At this point, therefore, the valley was occupied by ice to a very moderate depth, and it is the bottom portion only which betrays the curve of the U-section. In the higher Alpine valleys, on the other hand, — which were once filled to a much greater depth, — the steep undercut side walls often complete the form of the letter U. Their intersection with an earlier valley located

on the same general line, but at a higher level, has developed rather sharp shoulders. These remnants of the earlier valley are the *albs*, or high mountain meadows, so common along the Swiss valleys (see Fig. 27).

The form of these remnants of older and now higher valley floors, is not that of a water-worn valley, but generally is a relatively shallow glacier-carved trough. They, therefore, indicate that since sluggish glaciers carved the earlier valley, a new uplift of the range has taken place.[12] Subsequent to the uplift, the glacier acquired a steeper gradient and carved its bed below the middle of the older U-valley, as are the Norwegian valleys likewise to be explained through an uplift of the land.


FIG. 27. — Ideal cross-section of a U-shaped valley once occupied by a mountain glacier.

It is clear that the widening of the valley bottom is accomplished by the ice through the combined abrading and plucking processes. As is true of so many geological processes, the direct attack is here through a limited range only, but is extended upward and made more effective through undermining or sapping. The dividing line between the vertical zones of direct and indirect action — of ice erosion and of undermining — is often a sharp line. The upper zone quarried by the undermining process, here always greatly facilitated by frost rending, develops irregular but nearly vertical (joint) surfaces. The lower eroded surface, on the other hand, is rounded into shoulders (*roches moutonnées*), and is further smoothed and scratched (see Fig. 28 and plate 16 B). This line of sharp separation may be continued up the valley and there be joined to the schrund line of the cirque (see Fig. 6, p. 18).

*A.* The Little Cottonwood Canyon in the Wasatch Range transformed at the bottom into the characteristic U section.

(*After a photograph by Church.*)

*B.* Striated surface of glaciated valley floor near Loch Coriusk, Skye.

(*From a photograph by B. Hobson.*)

The areas of the valley section taken at different levels obviously stand in direct relation to the size of the glacier at those levels. When the glacier ended within the valley (dendritic glacier), ablation in the lower levels diminished

FIG. 28. — View in the glaciated Sierra Nevadas of California, showing the sharp line which sometimes separates the zone of abrasion from that of sapping (after a photograph by Fairbanks.)

the width of the ice-stream as its foot was approached. In some cases, the glacier never reached the margin of the upland, in which event the lower portion of the valley is relatively narrow and reveals the characteristic section of a river-carved valley. Even when widened by glaciation, the widest section may be found considerably above the lowest limits of the ice advance. This is illustrated by Big Cottonwood canyon in the Wasatch range, which at its portal is a narrow V-shaped valley, but which above has been widened by glaciation.[13]

Wherever, on the other hand, mountain glaciers have been

so amply nourished as to expand beyond the margin of the upland, the valley is found to widen rapidly towards its mouth and expands to the foreland in trumpet form. This is well illustrated by the portals of the larger Alpine valleys, which once supported piedmont glaciers (see Fig. 47, p. 85).

It has been urged, by those who regard the glacier influence as always protective to its bed, that the deep U-valleys have in pre-glacial or in inter-glacial times, been cut down by rivers, and that these narrow valleys the glaciers have subsequently widened. Some part the gorges of mountain streams must have played, particularly in inter-glacial times when the glacier-formed rock bars had been sawed through by the torrents which followed the retreat of the glacier from portions of its valley.

While nearly all glacialists seem to be agreed that a widening of valley bottoms results from the occupation by mountain glaciers, many are unwilling to admit that there is in addition, a deepening of the valley through the action of the same processes. To the present writer the evidence for the overdeepening inherent in the cross profiles of valleys is convincing.

FIG. 29. — Normal valleys from sub-aërial erosion — accordant drainage (after Davis).

**The Hanging Side Valley.** — Whereas under normal conditions of sub-aërial erosion, the individual tributary valleys meet the main valley at a common level, or accordantly (see Fig. 29), this is not true of glaciated valleys. Since the smaller tributary glaciers are unable to

erode their beds as effectively as the larger trunk streams, when both have been vacated by the ice, side valleys are found to have their beds standing above the general level of the main valley — they are not accordant as are the tributary valleys of rivers — and they are in consequence spoken of as "hanging valleys" (see Fig. 30). Unlike those tributaries which have never been occupied by glaciers, they are found to be too large for the streams which now flow in them. This stream drops over the steep U-wall into the main valley in the characteristic ribbon type of waterfall found in such numbers in every glaciated mountain district.

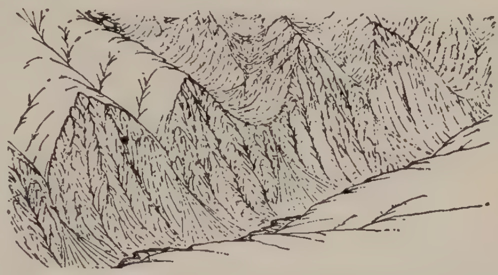

Fig. 30. — Glaciated and non-glaciated valleys tributary to a glaciated main valley. Both types of side valley are hanging (after Davis).

As pointed out by Penck, it is the *surfaces* only of main and tributary glaciers that are accordant, or at common level. It is, perhaps, profitable to consider for a moment why it is that the tributaries of water-streams should, under normal conditions, be accordant, as was long ago pointed out to be the rule by Playfair; whereas the *beds* of tributary glacier streams enter the main valley above the level of its floor. In both cases the tributaries are notably smaller than the main stream. The abrading process by which the water-stream lowers its bed is in no wise dependent upon the depth or volume of water, for water-streams have a cutting power directly determined by the gradient of their bed and increasing at a marvellous rate with increase of slope. Now tributary valleys in mountain districts have gradients which are much steeper than that of the main valley near the point of their junction (see Fig. 31).

In the glacier stream floor, gradient evidently plays a much less important rôle in the abrasion of the bed, while depth of ice would appear to be a determining factor, the

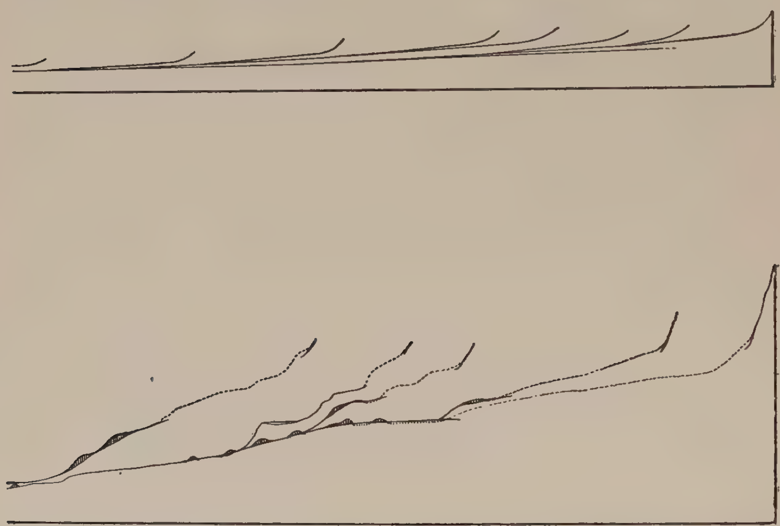

FIG. 31. — Comparison of the longitudinal profiles of a mature stream-cut valley and its tributaries with a glacier-carved Alpine valley and its tributaries. Note how in both instances the average gradient of the tributaries is always in excess of that of the main valley, near the junction (after scaled profiles prepared by Nussbaum[14]).

friction between the stones by which the glacier is shod and the rock floor causing a correspondingly greater wear. The hollowing of flagstones is proportional, not only to the number of footsteps which have come in contact with the stones, but also upon the weight of the individuals and the number of projecting nails upon their boot heels.

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[7] See also Nussbaum, "Die Täler der Schweizeralpen," Bern, 1910, pl. 2, figs. 2–4.

[8] Ed. Brückner, "Die glazialen Züge im Antlitz der Alpen," *l.c.*, 1910, p. 787; also Fritz Nussbaum, "Die Täler der Schweizeralpen, Eine geographishe Studie," Bern, 1910, 3 pls. and 12 figs.

[9] Brückner, *l.c.*, p. 787.

[10] De Martonne, "Sur la genèse des formes glaciares Alpines," *C. R. Acad. Sci.*, Paris, January 24, 1910, p. 1 (reprint).

[11] Brückner, *l.c.*, p. 790.

[12] Albrecht Penck, "The Origin of the Alps," *Bull. Am. Geogr. Soc.*, vol. **41**, 1909, p. 68.

[13] W. W. Atwood, "Glaciation of the Uinta and Wasatch Mountains," *Prof. Pap. U. S. Geol. Survey, No. 61*, 1909, pp. 85–88, pl. x.

[14] Nussbaum, *l.c.*, 1910, final plate.

# CHAPTER V

## HIGH LATITUDE GLACIAL SCULPTURE

**Variations in Glacial Sculpture Dependent upon Latitude.** — Thus far we have considered mountain glaciers in those districts which are most accessible for study, and hence are better known — mountain districts within moderate latitudes, in which the snow-line is from 7000 to 12,000 feet above sea, and where, in consequence, there is high relief and correspondingly steep gradients. Moreover, in most of these districts the surface upon which the mountain glaciers whose handiwork we may study, began their carving process was a surface moulded by the water-streams of a humid region — the initial surface in the glacial cycle was a product of sub-aërial erosion. The results are not in all respects the same in those higher latitudes where the snow-line descends to near the sea-level, and where in Pleistocene times, a continental glacier largely planed away the irregularities of earlier erosion periods, leaving a hard rock surface, but slowly acted upon by the well-known weathering processes.

The low level of the snow-line is here further responsible for the development of the subsequent mountain glaciers where there is only moderate relief, so that glacier streams developed on low gradients were notably sluggish in their movements. Inasmuch as the sub-polar regions particularly

have been characterized within the recent geological period by rather remarkable uplifts of the land, this elevation has had an important bearing on the origin of the surface features there developed.

**Surface Features of Northern Lapland.** — A visit to Northern Lapland is in this regard most enlightening to one who has observed glacial carving in lower latitudes only. In the lower levels of these Northern regions, which lie to the eastward, where the land was relatively low, and where the prevailing winds had already given up much of their moisture, mountain glaciers have, in consequence, found little to nourish them. Here is found to-day a surface of low, bare hills, rounded and smoothed and betraying the sculpture of continental ice masses alone (see Fig. 35 *a*).

Fig. 32. — Characteristic surface in Swedish Lapland which has been moulded mainly by the continental glaciers of Pleistocene times. The low central trough is, however, the work of a subsequent mountain glacier on a low gradient — the Kårso trough valley (after O. Sjögren).

The surface which still shows the features moulded by erosion beneath the continental glacier, would appear to extend far to the northeastward. To quote Feilden[1] on the Kola Peninsula: "As we sail eastward along the Murman

coast of Russian Lapland, we see on our right hand a bold and precipitous country. Its highest summits appear to rise to 500 or 600 feet. *The hills are planed down to a general level, and no peaked mountain breaks the monotony of the scene.*"[2]

**The Flatly Grooved Glacier Valleys and the Scattered Knobs.** — In the somewhat higher levels farther to the westward, but before the high Norwegian plateau is reached, the handiwork of mountain glaciers is recognized, though no ice masses are here in evidence to-day. Locally, where were centres of dispersion, the characteristic "arm-chair" form of the glacial cirque is to be seen, and well developed karlings are made out, though here the jagged pinnacles so common in lower latitudes, are seldom seen (see Fig. 33). Out from


Fig. 33. — Map of a portion of the area south of Torneträsk in Swedish Lapland showing the cirques and karlings developed by mountain glaciers subsequent to the continental glaciation.

these centres of late mountain glaciation, the sluggish glacier streams have channelled broad and gently hollowed grooves within the former undulating surface. These shallow valleys have but little in common with the deep U-channels

of the Alpine highland. Where these streams have been numerous and of nearly equal size, they have coalesced and so, to a large extent, have occupied the country, leaving a smoothed floor out of which more or less elongated knobs of rock rise on abrupt or even precipitous slopes (see Figs. 33 and 34). Where relatively large streams have channelled


Fig. 34. — Glacial surface crossed by shallow channels carved by sluggish mountain glaciers on a surface of slight relief. The area is south of Torneträsk in Swedish Lapland (after O. Sjögren).

the surface guided by pre-existing valleys, the horizon lines now show broad depressions resembling the bite of some gigantic monster. The *Lapporten*, or Lapp's Gate, which is seen in so many views about Torneträsk, furnishes a striking illustration (see Fig. 35 *b*).

**The Fjords of Western Norway.** — In the plateau region of Norway still further to the westward, where the heavier precipitation and the much higher elevations have made it possible for glaciers to persist to the present day, such flat U-channels may now be seen high up upon the level of the plateau (see Fig. 35 *c*). Similarly the steep-sided knobs (*nunataks*) which are found to characterize the relatively

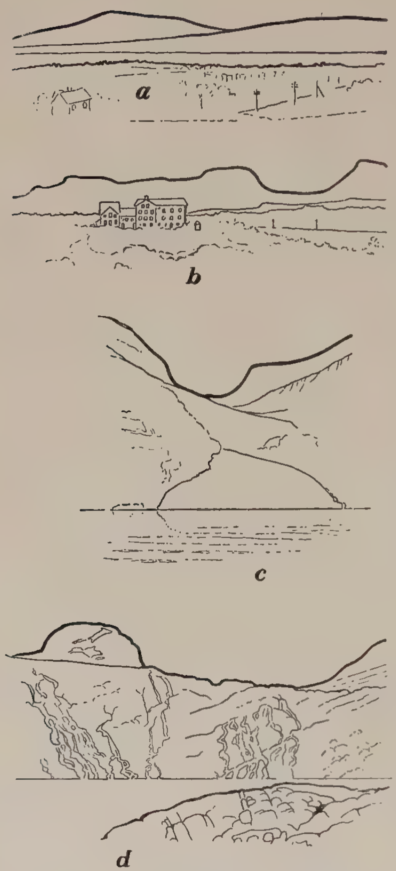


FIG. 35 *a.* — Characteristic surface contours in Eastern Swedish Lapland due to sculpturing by continental and mountain glaciers.

*b.* Horizon line showing the modification of surface moulded by continental glaciers, through the later work of sluggish mountain glaciers. The deep "bite" in the horizon line is the famous Lapp's Gate.

*c.* Flat U-channel on plateau of Western Norway; Geirangerfjord.

*d.* A steep rock knob rising from the plateau of Norway; Öxenelvene on the Nordfjord.

low surfaces of Swedish Lapland are here to be seen rising out of the level of the plateau (see Fig. 35 *d*).

In these sections of Scandinavia, the problems of glacial sculpture are much more complex, and are not to be solved by consideration of the latest glaciation only. As is now well recognized, the Pleistocene glaciation consisted of some four distinct glacial cycles, separated by inter-glacial periods which were characterized by relatively mild climatic conditions. An earlier submergence of the coast regions (see plate 17, B) has been followed by large and rapid uplifts, so that former strand lines are now to be seen high up upon the shores. Of the origin of the fjords — the deep and now partially submerged U-valleys — we know at least that their present form was given them when they were occupied by glacier streams;[3] and their definitely oriented arrangement further be-

trays the fact that the glacial excavation exercised a selective process on the lines of preëxisting fractures within the rocky basement, guided, perhaps, on these lines by earlier rivers which had first discovered these special lines of weakness within the earth's surface shell (see Fig. 36).

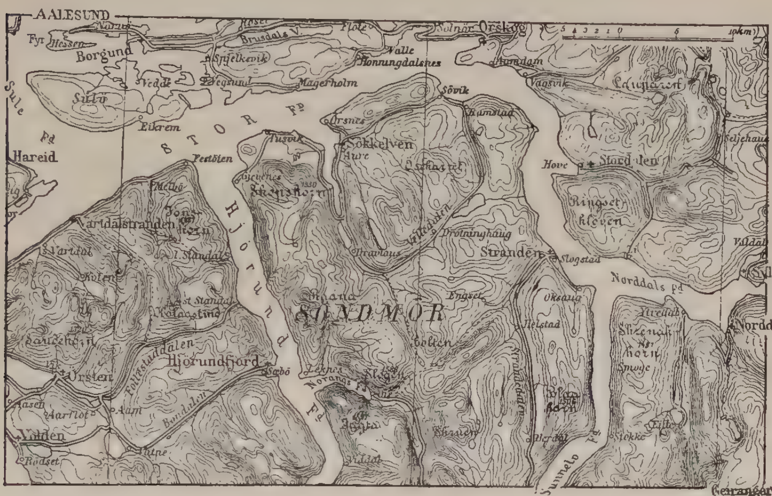



FIG. 36. — Map of the vicinity of the Storfjord in Norway, showing the regular arrangement of the fjords and submerged valleys in three principal parallel series separated by sub-equal space intervals.

**The Rock Pedestals bounded by Fjords.** — The late uplift of the coast subsequent to the formation of these deep fjords has raised veritable pedestals of rock surmounted by relatively flat surfaces, on which are revealed under exceptional circumstances the characteristic subdued forms found in the lower country of Northern Lapland (see Fig. 32, p. 71). Since these pedestals now lift their heads above the snow-line of the region, ice-caps are amply nourished upon them, so as often to more than cover the surface and spill over the edges wherever the margin has been notched by the earlier sculpturing. Near the centre of the *pedestal* the process of subglacial abrasion pares down the inherited irregularities,

whereas near the margins where the ice is thinner and the gradients are steeper, the inherited knobs have been greatly

FIG. 36 *a*. — Nunataks rising out of the surface of the Folgefond, an ice-cap of Southern Norway.

increased in height. Such a knob enveloped in the marginal portion of a Norwegian ice-cap is reproduced in plate 17 A

FIG. 37. — Erosional surface left within the marginal zone of a Norwegian ice-cap. The smoothly domed floor and the steep projecting knobs are characteristic. A moraine is in the foreground.

*A.* The Hardangerjökull, a plateau glacier of Southern Norway, where at its margin is seen the Kongsnut nunatak.

*B.* Upland sculptured by mountain glaciers and partially submerged through depression. Part of one of the Lofoten Islands.

*(From a photograph by Dr. L. M. Hollander.)*

and others appear in Fig. 36 *a*. Figure 37 shows, on the other hand, the site of such a margin to an ice-cap, after the

FIG. 38. — View of the Seven Sisters in Northwestern Norway, a series of ice-cap nunataks sharpened by the overflow of the glacier streams at the margin.

ice has retired. Here we find a smoothly polished surface descending on low gradients toward the margin of the pedestal. From this gently domed surface rise numerous knobs

FIG. 39. — Broad glacial trough overdeepened by the overflow glacier of later ice-cap.

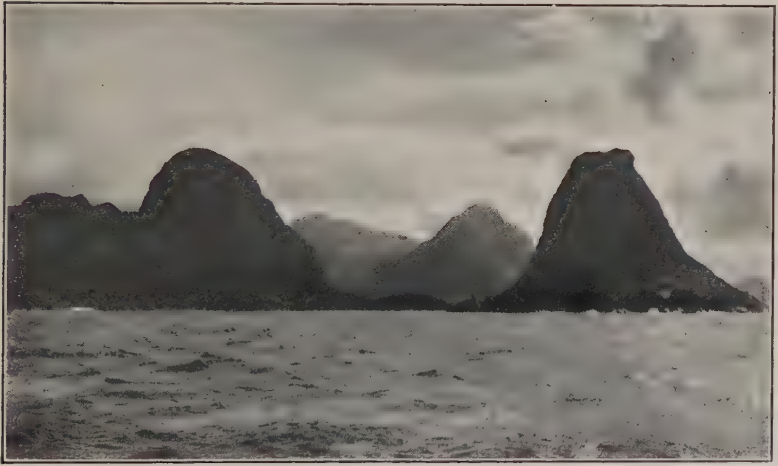
of rock, the marginal nunataks, though here the ice has not reached the margin of the pedestal so as to descend into the

surrounding fjords. (See pl. 34 A.) In Fig. 38 is seen another example where the ice has spread over the edge of its base and has deepened and widened the troughs upon its margins, thereby sharpening the intervening knobs.

Fig. 40. — Circular tind with acute apex from the Lofoten Islands. The Tennaes Tind, Kirkefjord (after a photograph by Dr. L. M. Hollander).

**The Norwegian Tind.** — Where the overflow streams on the margin of the ice-cap are of notably smaller dimensions

*A*. The Fjaerlandsfjord on the margin of the Jostedalsbräen, showing the nunataks inherited from an earlier cycle as they develop into *tinds* by the overflow ice streams deepening the channels which separate them.



*B*. Nkkerne, Vesteraalen. Typical *tinds* formed on the margin of Norwegian plateau glaciers. A later product of the process shown above, in *A*.

than their predecessors of an earlier cycle a sharp shoulder has developed on either side of the valley (see Fig. 39). The deepening of the channels of small overflow glacier streams, if continued, so lowers the marginal channels as to transform the inherited nunataks into high peaks sometimes having the form of bee-hives, on which the sharp change in slope marking the transition from the earlier to the later sculpture can often be made out. In plate 18 A an existing Norwegian glacier is seen modifying the nunataks in this manner, while in B of the same plate the later effect of the process is to be observed. These steep rounded peaks are the characteristic *tinds* of the Norwegian coast. They are markedly circular at their base, they rise at first on excessively steep slopes, but at greater heights take on gentler gradients, often showing a sharp change in curvature, as is indicated in plates 18 B and 34 B.

In the Lofoten Islands, a western outlier of the Norwegian plateau to the north of the Arctic circle, tinds have developed apparently by this process, though they have here taken a sharply conical form with almost circular base, so that they resemble in form the point of a well-sharpened pencil (see Fig. 40). Inasmuch as these develop in a massive

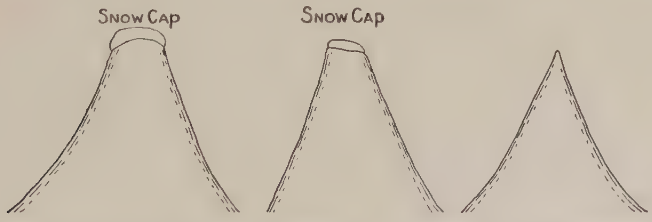



Fig. 41. — Successive diagrams to illustrate a theory of the shaping of acute circular tinds through exfoliation.

igneous rock, a gabbro, and the surfaces indicate clearly that the forms are now being shaped as a result of heavy exfoliation, a suggestion may be hazarded with regard to the latest

stages of their evolution. A tind shaped by overdeepening on the margin of an ice-cap (see plate 18 B and Fig. 41) is by reason of its steep sides able to support snow only upon its summit. About its flanks the tind is scaled off and rendered circular in plan. The protecting snow-cap[4] prevents this action at the top, but this cap is melted at its margin where warmed by radiation from the neighboring rock surface. The water derived from this melting enters all cracks due to exfoliation, thus greatly facilitating the process and preventing the formation of an overhanging rock cornice. The stages of the process are suggested in the diagrams of Fig. 41.

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[2] The italics are mine. — W. H. H.

[3] Fr. Machaček, "Geomorphologische Studien aus dem norwegischen Hochgebirge," *Abh. d. k. k. geogr. Gesellsch. in Wien*, vol. **7**, 1908, pp. 1–61, 11 pls. and a map.

[4] In the long winter season.

# CHAPTER VI

## GLACIAL FEATURES DUE MAINLY TO DEPOSITION

**Abandoned Moraines of Mountain Glaciers.** — Not only do we find in valleys the marks of former occupation by mountain glaciers in characteristic erosional forms — the cirque, the *roches moutonnées*, the U-valley, and the hanging side valley — but in many cases, at least, the evidence is supported by characteristic glacial deposits. These deposits are naturally less in evidence in the higher levels, where erosion has been more active; but toward the lower reaches the importance of glacial deposits rapidly increases. With the retirement of the glacier up its valley, medial and ground moraines come alike to occupy the valley floor, though the talus and landslide conspire to cover the lateral portions from sight.

Fig. 42. — Terminal and lateral moraines remaining from earlier mountain glaciers which pushed out upon the flanks of the Sawatch range (after W. H. Holmes).

Wherever the glaciers have pushed out upon the foreland, and there been halted for considerable periods, the lateral and terminal moraines have been left as definite and often well marked topographic features (see Fig. 42). Such terminal

moraines at the mountain front sometimes show the contours of the expanded foot, and quite generally also the first series of recessional moraines (see Fig. 43 and plate 15).

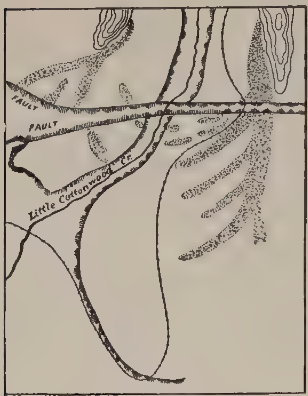



FIG. 43. — Sketch map of the morainic ridges near the mouth of Little Cottonwood canyon of the Wasatch range (after Atwood).

Within the valleys and back from the front of the range, glaciers have also left behind them series of recessional terminal moraines to mark the principal halting places during their retreat. These moraines in many cases hold back the water of the valley stream, forming morainal lakes, as, for example, in Parker Canyon of the Sierra Nevadas (see plate 15), or Convict Lake within the same general region (see Fig. 44).

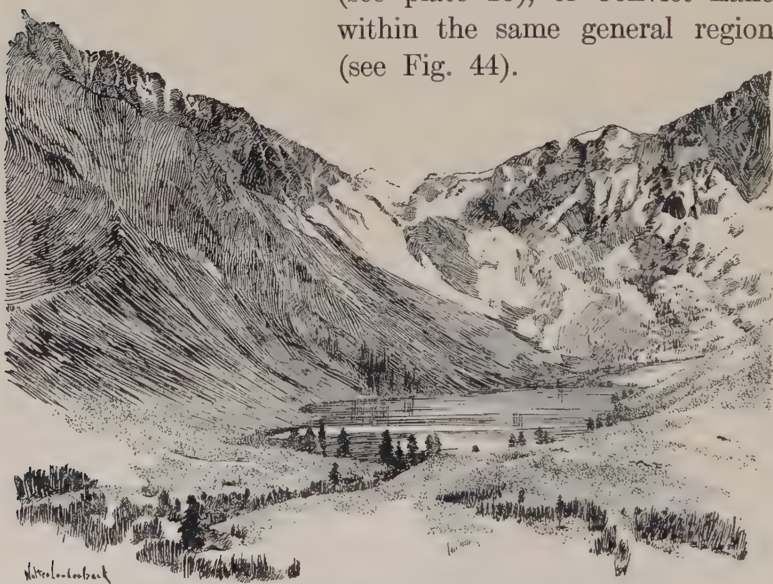


FIG. 44. — Convict Lake, a lake behind a morainal dam in a glaciated valley of the Sierra Nevadas in California (after a photograph by Fairbanks).

**The Tongue-like Basin before the Mountain Front.** — Wherever with ampler nourishment glaciers have coalesced and expanded to the proportions of the piedmont type, the marginal moraine has acquired formidable dimensions and may be miles in width, and of considerable height.[1] The width of this ice deposit is extended toward the interior of the ice-apron by a zone of drumlins — cigar-shaped hills of till whose longer axes are perpendicular to the moraine.[2] Thus is built up a tongue-like basin often with subordinate marginal lobes, within which the glacier-apron rested (*Zungenbecken* of Penck). Such a basin is shown in Fig. 49, p. 88.

**Border Lakes.** — The study of the glaciers which in Pleistocene times pushed out from the portals of the Alps upon the


Fig. 45. — Map of the moraines and drumlins within and about the apron of the piedmont glacier of the Upper Rhine (after Penck and Brückner).

Swiss and Italian forelands, has proved most illuminating. In Fig. 45 is reproduced a map of the moraines formed about the apron of the great piedmont glacier which once occupied

the valley of the Upper Rhine and a portion of its foreland. The central area of this basin is now occupied by the beautiful Lake Constance, which in an earlier and higher stage extended past the border of the foot-hills into the Alpine valley. Such lakes are found in many similar sites of piedmont ice-aprons on the borders of the Alps, and have been referred to as border lakes (*Randseen*). Heavy morainic accumulations hem them in upon the outer margin, and their waves lap the rising slope of the glacier valley within its gateway. An instance in which the plan of the lake brings out with especial clearness the relatively narrow valley and the expanded form of the ice-apron without, is Lake Garda (see Fig. 46). Geologically considered, lakes are, however, notoriously short-lived, and the basins of extinct lakes are found at the portals of most of the larger Alpine valleys which have not existing lakes.[3] The con-


Fig. 46. — Lake Garda in a southern gateway to the Alpine highland expanded over the apron site of the earlier piedmont glacier (after Penck and Brückner).

ditions on the northern border of the Alps are brought out in Fig. 47.

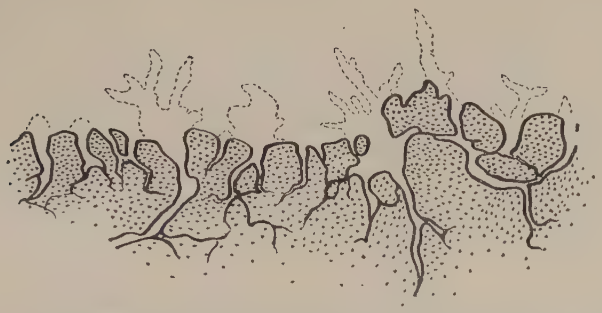


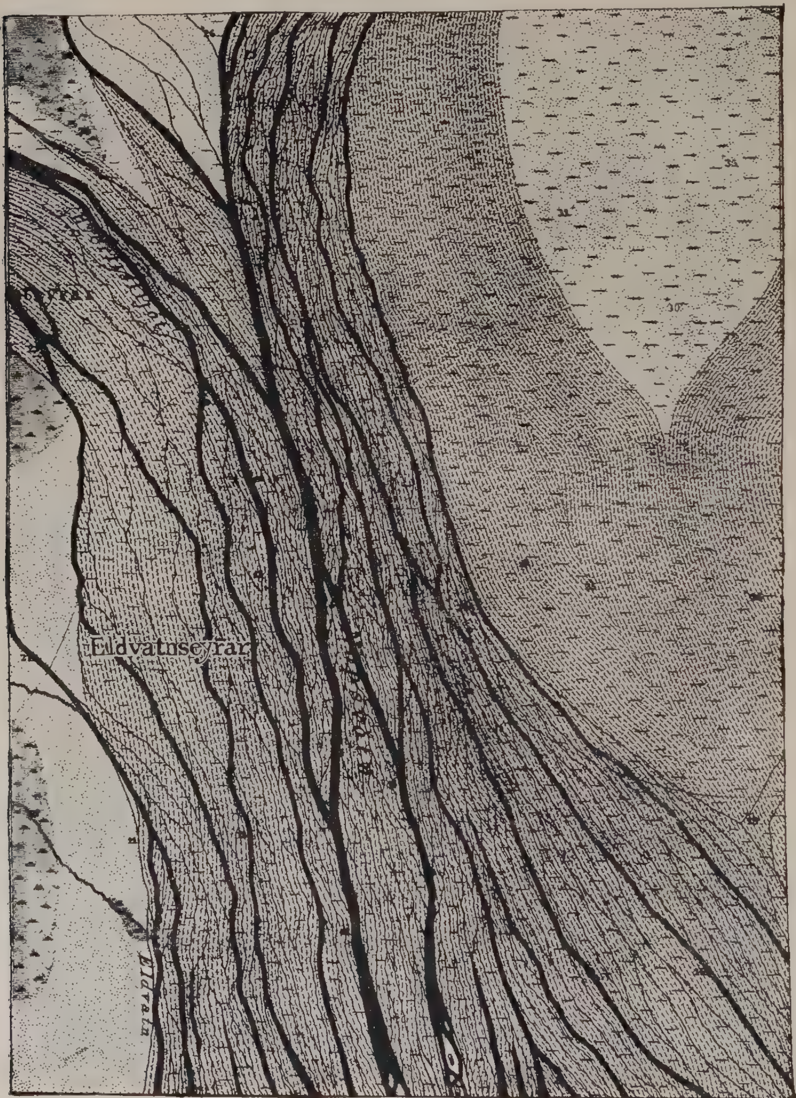
FIG. 47. — Outline map of the northern border of the Alpine highland showing the basins of former lakes. The trumpet-like widening of the valleys at their mouths should be especially noted (based on a map by Brückner).

Tongue-like basin lakes within the apron site of former piedmont glaciers would appear to have been characteristic also of the piedmont glaciation in the northern Rocky mountains of Montana.[4]

**Stream Action on the Mountain Foreland.** — Wherever glaciers are so large as to expand upon the foreland to the range which furnishes their nourishment, they build up, as has been seen, a broad rampart of morainic rock débris which later marks the limit of their advance. The constancy of occurrence and the magnitude of these deposits from the ice near its margin, testify to the gradual change from increasing rigor of climate to a progressive amelioration of these conditions. No less significant in this respect are the heavy deposits which outside the marginal moraine have been distributed by streams of water from the glacier.

Most of this water emerges from beneath the ice, though much of it may have flowed upon the glacier surface for greater or less distances until permitted to descend through crevasses to the bottom. Russell's study of the Malaspina glacier of Alaska, the one existing example of a piedmont

glacier that has been carefully studied, showed that streams of water from near the upper edge of the ice-apron there




SCALE: 1 in. = $1\frac{1}{8}$ mi.

FIG. 48. — A braided stream which flows from the margin of the Vatnajökull in Iceland. (From the new map by the Danish General Staff, 1905.)

disappeared into tunnels within the ice to be lost to sight until their reappearance at the outer margin.

The water of these streams is in the lower levels held within the ice as within a pipe, and is in consequence under strong hydrostatic pressure. Its flow is, therefore, much more rapid than would be the case with a liquid having a free surface. In fact, it could not otherwise ascend the slope which we have found to be characteristic of the outer portion of the tongue-like basin beneath the ice-apron.

**The Outwash Apron.**—Emerging from beneath the ice, the flow is suddenly checked and the stream being overloaded with rock débris, this is quickly deposited as sediment, the coarser materials nearer the ice margin and the finer ones at greater distances. Thus is built up a broadly extended outwardly sloping platform composed of water-deposited materials, which platform surrounds the glacier and its marginal moraine as an *outwash plain* or *outwash apron.*

Over the nearly level surface of the outwash apron, the streams flow in ever shifting serpentine courses, and are joined to their neighbors on either side only to divide the waters of the combined streams at the first minor obstruction that is encountered. Such composite streams may be compared to the strands of a braid, and they have been described as "braided streams" (see Fig. 48). The width of such a stream, or perhaps better, series of streams, may be as great or even greater than the individual length. Constantly shifting their courses through lateral migrations, such rivers grade the plain on which they flow to the evenness of a well-sanded floor. This peculiarity and their location just without a marginal moraine (see Fig. 49) make the later determination of such plains a relatively easy matter.

**Eskers and Recessional Moraines.**—To indicate their relation to glaciers as well as to describe their deposition by

streams, outwash deposits are referred to as "fluvio-glacial." They are sands and gravels imperfectly stratified and having included lenticular masses of coarser and finer materials.

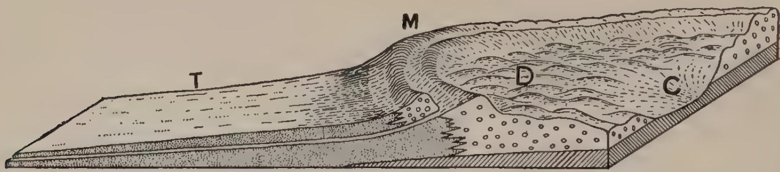



FIG. 49. — Ideal form of a tongue-like basin remaining on the site of the ice apron of a piedmont glacier and surrounded by the outwash apron. *M*, marginal moraine at outer limit of ice advance; *D*, drumlins; *C*, basin usually occupied by lake; *T*, outwash plain of fluvio-glacial deposits (after Penck).

Russell has described streams which issue from the margin of the Malaspina glacier with such velocity that the sudden checking of their current causes the deposit of relatively coarse materials in a steep apron resembling in form the dry deltas of mountain fronts within semi-arid regions. He points out that a continuance of such streams during a recession of the glacier would build up a serpentine ridge of water-deposited materials whose average course would be perpendicular to the marginal moraine.[5] Such ridges, known as "eskers," have not been reported from the sites of the Alpine piedmont aprons,[6] though they appear to have formed under somewhat similar conditions along the east front of the Rocky mountains in Montana.[7]

It should not be overlooked that while Russell's observations make it probable that eskers are now forming in the tunnels beneath the ice apron and behind the alluvial fans which block their outlets, the eskers do not appear outside the ice front. Tarr, who has confirmed Russell's conclusion, thinks that the active stream erosion at the ice front would destroy the esker as fast as it was uncovered, and that eskers have become visible only where the ice ended in bodies of standing water or else had become rela-

tively stagnant.[8] The former case would apply to the osar of Sweden, and the frequent termination of eskers in delta-like sand plains with relatively flat upper surface and steeply sloping margins, would likewise favor this view.

With the commencement of the receding hemicycle of glaciation, the ice front retires from its marginal moraine and eventually enters the mountain valley, though usually leaving behind it a series of smaller and so-called "recessional moraines" to mark successive and relatively short halting places during its retreat. The uncovered site of the former ice-apron is, as we have seen, a basin, so that this is filled with water from the melting of the ice during the retreat to the mountain front. The water thus impounded finds its outlet at the lowest level of the morainal crest, and being already filtered of coarser material by the lake itself, this outlet rapidly cuts a channel through the loose materials of the moraine and its bordering plain of fluvio-glacial deposits. Thus sections are exposed to view revealing a history of the glacier whose episodes are to be compared with those disclosed by the plan of the valley above when it has likewise been laid bare.

**Stream Action within the Valley during the Retirement of the Glacier.** — The "glacier staircase" left by the ice, with its rock-basin lakes high up in the valley and its morainal lakes within the lower reaches, undergoes a rapid transformation under the influence of running water so soon as the ice has largely vacated the valley. Flowing from the waning remnant of the glacier, this water is overburdened with sediment. Its current is sluggish over the treads of the steps, but develops cascades over the cliffs between. The coarse débris which it carries is thus quickly dropped upon the treads to fill the lake basins, and with the aid of the finer material as tools, the rock obstructions are cut through in narrow canyons and with a marvellous rapidity. Where a

barrier of more resistant rock has hemmed in a portion of the valley (*Riegel*), narrow and picturesque gorges have been cut, such as the *Aarschlucht* and the gorge of the

Fig. 50. — Gorge of the Albula river, near Berkun, in the Engadine.

Gorner. Tyndall has described many of these interesting gorges within the "European playground."[9] One of the finest illustrations is furnished by the Albula River, near Bergun, in the Engadine (see Fig. 50). Here the glaciated valley with its characteristic U-section, is at the top of the narrow gorge, which latter, therefore, represents the work of the stream since the retirement of the glacier.

**Landslides and Rock Streams within the Vacated Valley.** — Perhaps the most general characteristic of regions which have in recent times been sculptured by mountain glaciers is the dominance of the precipitous rock face — the walls of the fretted upland. To-day, wherever rock climbing is indulged in, there glaciers are to be seen, or the evidence of their former presence is everywhere overwhelming. It is the sapping process active in cirque recession and in valley widening which has here developed the nearly vertical rock face.

Obviously such steep surfaces are unstable under existing conditions of weathering within humid regions, and can long retain their forms only under the most favorable circumstances. Until the glacier vacated the valley, the walls were in part supported at least toward the base by the ice itself. On the Vernagt and Rhone glaciers a sliding down of the walls has begun in the parts but lately left unsupported.[10] If of weak or porous materials, or if intersected by many planes of ready jointing or cleavage, such precipitous faces become an easy prey to frostwork and rock slide. For these reasons, glaciated valleys within mountain districts have often been the scenes of disasters from avalanche. Wherever the rock is of a porous nature or has open structures, water gradually comes to fill all the spaces within the material, at least along certain planes favorable to its entry. After a time prodigious masses of rock suddenly descend under the influence of gravity, and within

the space of a few seconds, or at most minutes, they have either partially or wholly blocked the valley, leaving great scars to mark their former positions.

The landslide of Frank, Alberta, which occurred in 1903, near where the southern line of the Canadian Pacific Railroad enters the Crows' Nest Pass of the Rocky Mountains, was the movement of a mass of loose earth a half mile square and between 400 and 500 feet in thickness. Only about a minute and a half after this mass started from a shoulder of Turtle Mountain, it had travelled two miles and a half and been spread over a square mile of valley bottom.[11] Farther south in the Rocky Mountains, and in Colorado particularly, are numerous relics of former great slides.[12] Here the insecure foundations of massive rocks and a jointed and shattered condition of these rocks themselves has facilitated the entrance of water within the rock mass and greatly promoted avalanching.

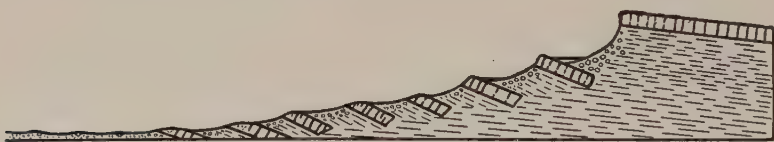


FIG. 51. — Ideal section showing successive slides from a canyon wall producing a staircase effect with back-tilted treads (after Russell).

How important the vertical joint planes may be in the settling away and eventual fall of the valley walls is shown to advantage in the Ötzthal of Switzerland, where, in the angle between the Vernagthal and the Rosenthal a little above the height of the glacier surface at its maximum, the wall is now settling down in sections separated by joint planes so as to produce the form of a staircase.[13] These conditions are, moreover, common to all high vertical cliffs, and Russell long ago pointed out that successive slides take place from steep canyon walls in such a manner as to

produce a staircase effect with back-tilted treads (see Fig. 51).[14]

From the glacial valleys of Switzerland many examples of great landslides have been supplied. In 1881 the town of Elm in Canton Glarus was overtaken by a slide from the Plattenbergkopf, which had been partly undermined in a slate quarry. About twelve million cubic yards of rock fell a distance of about 1500 feet, shot across the valley and up the opposite slope to a height of 300 feet, and being there deflected spread over a broad plain in a sheet which had an area of a million square yards. Over the range from Elm

Fig. 52. — View of the succession of rock slides from the north wall of the Upper Rhine near the town of Flims.

and above the town of Chur in the valley of the Upper Rhine is the site of a veritable succession of slides from the valley wall, known far and wide as the *Flimser Bergstürz* (see Fig. 52).

Many of the apparent steps in the transverse sections of Alpine valleys[15] are to be explained through landslides of this nature.

**Rock Flows from Abandoned Cirques.** — Long after the waning horseshoe glaciers have disappeared from glacial amphitheatres, the winter snows will there be collected and persist through a portion, at least, of the summer season. The same conditions of excessive frost weathering, which we have become familiar with in the process of nivation and of cirque recession within the same levels must, therefore, long continue to exist. Essentially the same conditions may be said to be characteristic of those other and vaster inhospitable areas of the sub-polar regions which are uncovered by ice and have but a thin covering only of snow. For these districts the mechanical process of rock rending and comminution is as characteristic as the chemical process of decomposition within a warmer humid region.

After the rending of the rock materials has been accomplished, gravity becomes effective to bring about a transfer of material to the lower levels by a process of rock flow which has been called "solifluction."[16] To this flow of rock débris belong many of the properties either of water or of ice-streams, and the moving masses have in different districts been called "mud rivers," "stone rivers," "rock flows," "rock glaciers," etc. Together with this flow goes also, under certain conditions, a peculiar striping of the surface of the ground,[17] and as this occurs only below a drift of snow, the function of the thaw water in giving the mass its property of flow is at once apparent. It is well to emphasize, then, that the thaw water from the melting snowdrift determines both the nightly freezing and rending of the rock, and the fluxion of the rock mass as well.

Outside the inhospitable sub-polar regions it is the abandoned glacier cirques which, largely because of their high altitude and their peculiar form, best supply the conditions requisite to solifluction. Within the San Juan Mountains of Colorado, the high glacial cirques are many of them occu-

pied by somewhat remarkable rock streams.[18] The position of two of these rock streams relative to the neighboring cirque walls is brought out in Fig. 53 and in plate 19, A

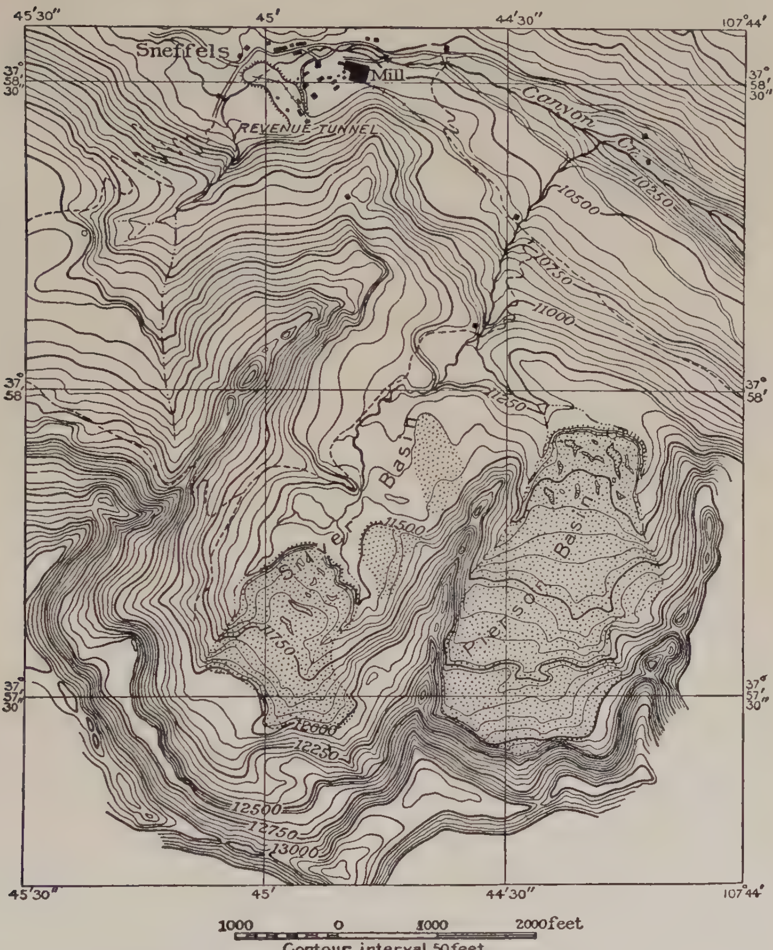



FIG. 53. — Map of two high glacial cirques now partially occupied by rock streams. The dotted areas are rock streams (after Howe).

and B. The rocks are here, by reason of their loose foundation, of their open joints, and their steep forward grades,

most favorable to the entrance of water, and the subsequent fall of the rock materials.

In the mountains of Alaska so-called "rock glaciers" occur which have much in common with the rock streams of Colorado. Rock glaciers are mixtures of ice and rock, sometimes passing upward into glaciers of ice and having in lower levels a surface coating only of angular rock débris.[19]

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*A.* Rock stream in a cirque on Greenhalgh Mountain, Silverton quadrangle, Colorado (after Howe, U. S. Geol. Survey).

*B.* Rock stream at the head of a cirque in the Silver Basin, Silverton quadrangle, Colorado (after Howe, U. S. Geol. Survey).

# PART II

# ARCTIC GLACIERS

## CHAPTER VII

### THE ARCTIC GLACIER TYPE

**Introduction.** — As elsewhere pointed out, continental glaciers are in other than dimensional respects sharply differentiated from those types which have been described as mountain glaciers.[1] The ice-cap glacier, while of smaller dimensions than the true inland-ice or the continental glacier, is physiographically allied with this type, and has few affinities with mountain glaciers. The sharpness of the distinction has often been overlooked for the reason that true mountain glaciers frequently exist within a fringe surrounding the larger areas of inland-ice, both in the Arctic and Antarctic regions. The distinguishing difference between mountain glaciers and continental glaciers is one primarily dependent upon the proportion of the land surface which is left uncovered by the ice, and the position of this surface relative to the margins of the snow-ice mass. *With true mountain glaciers land remains uncovered above the highest surfaces of the glacier, where, in consequence, a special erosional process — cirque recession — becomes operative.* The smaller ice-caps take their characteristic carapace form and cover the surface of the land within their margins, because that surface is relatively level. Had it been otherwise, the same conditions of precipitation would have yielded mountain

glaciers in their place. The law above stated is none the less applicable, since, because of this flat basement, no land projects above their higher levels.[2]

There are, as we shall see, other attributes which strikingly differentiate the large continental glaciers from all other bodies of land ice. These relate particularly to the nature of the snow which feeds them, to changes which that snow undergoes after its fall, to the manner of its transportation, etc. Most of these differences are of such recent discovery, or at least of such recent introduction into the channels of dissemination of science, that they have not yet found their way to the student of glacial geology. We shall profitably begin our description of continental glaciers with the intermediate ice-cap type, so as to establish connection with mountain glaciers in the important condition of alimentation. Before doing so, it will be well to call attention to some contrasts which exist between the north and south polar regions in those conditions upon which glaciation depends.

**North and South Polar Areas Contrasted.** — A glance at a globe, which sets forth the land and water areas of the earth, is sufficient to show that the disposition of land and water about the opposite ends of the earth's axis is essentially reciprocal. About the north pole we find a polar sea, the Arctic ocean, surrounded by an irregular chain of land masses which is broken at two points, nearly diametrically opposite. In the Antarctic region, on the contrary, it is a high continent which is massed near the pole, and this is bounded on all sides by a sea in which are joined all the great oceans of the globe save only the Arctic. This polar continent is deeply indented on two nearly opposite margins, but to what extent is not yet known. The margins of the continent are extended beneath the sea in a wide continental shelf or platform. The broad encircling ocean,

while to some extent invaded by the southern land tongues of South America, Africa, Australia, and New Zealand, is yet so little occupied by land masses that wind and ocean currents are alike but slightly affected by them. The Antarctic conditions are, therefore, oceanic — characterized by uniformity and symmetry to a much larger extent than is true of the northern polar region.

Within the northern hemisphere a large quantity of heat from the tropics finds its way northward to the breaks in the northern land chain, through the medium of great ocean currents — the Gulf Stream in the Atlantic, and the Japanese Current in the Pacific. Cold return currents from the Arctic region, and the widely different specific heats of land and water, coöperating with the effect of the northward-flowing warmer currents, result in a marked diversity in temperature, winds, and precipitation at different longitudes within the same latitudes. Lack of symmetry in distribution and wide variations in climatic conditions are, therefore, characteristic of the north polar region; and it follows that the present glaciation of the northern hemisphere is localized within a few scattered areas where the land projects farthest toward the pole, and near where there are sea areas of excessive evaporation to supply the necessary moisture.

**The Fixed Areas of Atmospheric Depression.** — Examination of Fig. 54 will show that the areas of existing heavy glaciation in the northern hemisphere lie close to the so-called fixed areas of low barometric pressure, each of which is a long, curved trough, concave to the northward, one central over the Aleutian Islands' Arc at the northern bight of the Pacific ocean, the other extending from the southeastern extremity of Baffin Land past Cape Farewell, and northeastward across Iceland, so as to occupy similarly the northern bay of the Atlantic ocean. For such northern latitudes, these areas of fixed low barometric pressure are

in consequence characterized by abnormally large evaporation. Wherever the moisture-laden winds proceeding from these areas are forced to rise by upland barriers, or to come

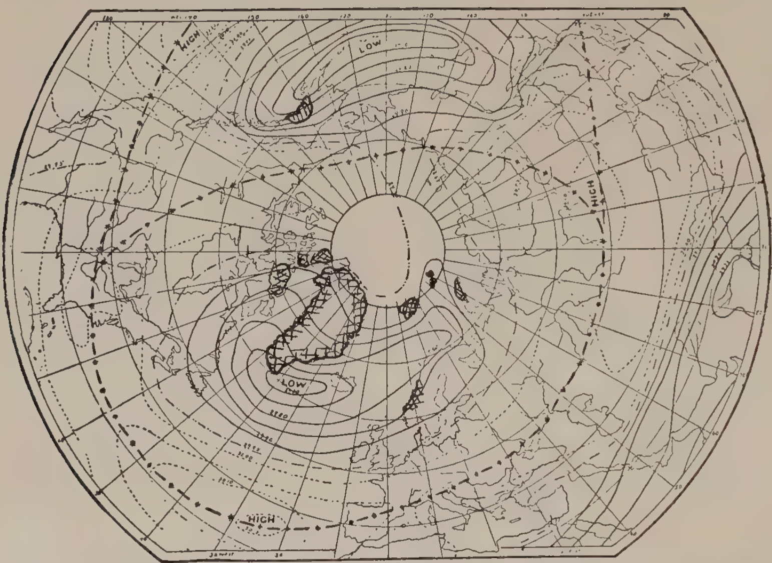

FIG. 54. — Map showing the areas of fixed low barometric pressure in the northern hemisphere (after Buchan). The areas of heavy glaciation have been added.

in contact with cold rock or snow surfaces, condensation and precipation must inevitably take place.

The prevailing westerly winds from the Pacific, when they encounter the high backbone of the Cordilleran System of mountains in Alaska nourish the great mountain glaciers of that region. The Cordilleras of Alaska are, however, competent to arrest but a small portion of these moisture-laden clouds, for it is only in moderate latitudes that they bar the way, and no highlands lie beyond them to the eastward until the vicinity of Baffin Bay has been reached.

On the border of the Atlantic low pressure area are found Greenland, Iceland, Spitzbergen, Norway, Franz Josef Land and Nova Zembla, each with its upland areas and its exist-

ing glaciation. In Norway, Iceland, and Franz Josef Land we find ice-caps; in Spitzbergen, Nova Zembla, Baffin Land, Grinnell Land and Ellsmere Land, the mantle of snow and ice is best described by the name "inland-ice," while upon the continent of Greenland the inland-ice has continental dimensions, and forms one of the two continental glaciers that still exist.[3]

*Of all the northern ice-sheets, with the exception of the archipelago of Franz Josef Land, the rule holds that they are smaller than the land masses upon which they rest,* and this in part expresses the difference between the northern and southern types of inland-ice.

**Ice-caps of Norway.** — In contrast with all save the piedmont type of mountain glaciers, the snow-fields of ice-caps


FIG. 55. — Idealized section showing the form of "fjeld" and "brae" in Norwegian ice-cap.

are much the larger. Speaking broadly, high and relatively level plateaus, light winds, and low temperatures are favorable to the existence of ice-caps. To-day they are not to be found in latitudes lower than 60°. In Norway, within the zone of heavy precipitation along the western coast, and upon the remnants of the plateau separated by the fjords are still to be found a number of small ice-caps. These caps consist of a central carapace of snow and ice from the borders of which narrow tongues descend into the fjords. The largest of these ice-caps is the Jostedalsbräen, having an area of 1076 square kilometers. Whereas with mountain glaciers the *névé* is contained within a basin, the cirque, we here find the so-called "fjeld" nearly level and resting

upon the surface of the plateau. Of this fjeld broadly lobate extensions lie upon its margin separated by deep valleys or fjord heads. Much narrower extensions of the central carapace often descend the steep slopes at the upper end of these valleys and may continue down the valley floor. Their narrowness is largely explained by their more rapid motion upon the steeper slope and by the radiated heat from the rock walls on either side (see Fig. 55 and plate 20).[4] Near the margins of the ice carapace, the subjacent terrane sometimes makes its appearance as rocky islets or nunataks, as, for example, in the Hardangarjökull near Finse in Southern Norway (see plate 17 A).

**Ice-caps of Iceland.** — In Iceland are to be seen some of the finest examples of ice-caps that are known, and, fortu-


Fig. 56. — Maps of the Hofs Jökull and the Lang Jökull (after Thoroddsen).

nately, these have been carefully studied by Thoroddsen.[5] These ice-caps form gently domed crests or undulating ice-fields situated upon the highest plateaus which rise above the general table-land of the country. Projecting mountain peaks appear with few exceptions only near the thinnest


*Portion of the new map of the Jostedalsbräen, which displays the characteristic plan of the surface physiography.* The glacier sends out lobes upon the flat parts of the spurs between fjords, and elsewhere descends in long, narrow tongues into the fjords themselves, here dimpled above the fjord heads through indraught of the ice.

margins of the ice, where they form either comb-ridges or sharp peaks (see Figs. 56 and 57). White and altogether free from surface rock débris except in the vicinity of their margins, these ice-caps offer in this respect additional contrast to mountain glaciers. The largest of the Iceland ice-caps is the Vatna Jökull, which has an area of 8500 square

Fig. 57. — Map of the Vatna Jökull (after Thoroddsen).

kilometers, while the surfaces of the Hofs Jökull, Lang Jökull, and Myrsdals Jökull, each exceed a thousand square kilometers. The shield-like boss of the Vatna Jökull is brought out in the section of Fig. 58.[6]

Those borders of this ice mass which lie upon the plateau, the northern and western areas, are broadly lobate; but upon the southern and eastern margins, where the ice mass descends to lower levels and approaches the sea, its tongues sometimes end a few metres only above sea-level. It is noteworthy, however, that where deeply incised valleys invade the plateau upon this margin, the lobes of ice push out mainly upon the upland remnants between the valleys,

though they send narrow tongues down the valleys themselves. This, as we shall see, is a peculiarity which ice-caps and the northern inland-ice as well, have in common to distinguish them further from mountain glaciers. As was found true of the Norwegian glaciers, so here the tongue which follows the valley bottom and which partakes of many of the properties of a mountain glacier, is much the narrower.[7]

From comparison with the Antarctic ice masses, these rapidly moving extensions of the central mass through rock gateways may be designated "outlets" (see Part III, p. 186). This peculiarity of ice-caps is well displayed upon the General

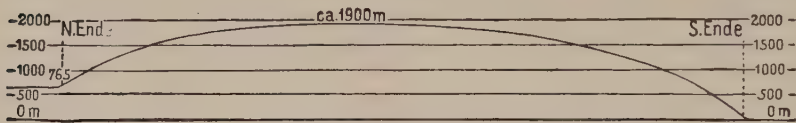


FIG. 58. — Cross section of the Vatna Jökull from north to south (after Thoroddsen and Spethmann).

Staff Sectional Map of Iceland, on scale 1:50,000 now in process of publication. The sections which include the Icelandic ice-caps show, not only the contours of the ice surface, but, further, the nature of the crevassing, and they are probably the finest glacier maps which have thus far been issued. Plate 21 reproduces on a reduced scale, a portion of section Oraefajökull.

From the north or plateau margin of the Vatnajökull, flow mighty but sluggish streams which, near the glacier, are braided into constantly shifting channels within a broad zone of quicksand. In this sand, horse and rider, if once entangled, are quickly lost. Upon the south margin, on the other hand, the streams from the melting of the ice flow as series of fast rushing rivers, sometimes so broad as not to be bridged, and in these cases setting up impassable barriers between districts (see Fig. 48, p. 86).

Icelandic ice-caps differ from all well-known glaciers at


*Map of the margin of an Icelandic ice-cap.* The tongue-like streams of ice in valleys and the apron-like extensions on the plateau level are shown (from the General Staff map, section Oraefajökull, 1905). The north side is here at the bottom of the map.

least in this, that nowhere else are large ice masses in such direct association with so active volcanoes. The *jökulhlaup,* which is the Icelandic name applied to one of the characteristic catastrophies of the island, occurs whenever a volcano, either visible in the neighborhood of the glacier or hidden beneath it, breaks suddenly into eruption. The first intimation that such an event is transpiring, is often the drying up of a stream which flows from the affected region. Sometimes the people are permitted to see great masses of lava and volcanic ash issue together from the glacier. All at once, the stream which had first dried up comes rushing down its valley as a foaming flood of water, spreading out for miles and having a depth sometimes as great as 100 feet. The entire plain is then spread with mud and sown with great rocks and also with ice blocks, some of which are as large as the native houses. These ice blocks are often buried in the mud, and later, when they have melted, they leave deep pits in the plain similar to, though smaller than, the depressions in a "pitted plain" from the continental glaciers of Pleistocene time. The "glacier run" of 1903 produced pits (*Sölle*) in the *Skeitharár Sander.* In 1904 the partially melted blocks of ice were to be seen in the pits.[8] It is not, of course, here assumed that the cause of the pits of the Pleistocene sand plains are in any way connected with volcanic action, but only with the burial of ice blocks under rock débris. Tarr has described the formation of such plains in front of the Hidden glacier of Alaska, where the melting ice margin is becoming buried beneath its own burden of rock débris and is locally opened up in pit lakes.[9]

During a volcanic eruption, water is seen to shoot up from the glacier in great jets, and it has sometimes happened that the entire ice mass of the jökull has been shattered, and a chaotic mass of ice miles in width has slipped resistlessly down the slopes. With the conclusion of the disturbance, the as-

pect of the entire district is sometimes found to be utterly changed. All vegetation has been destroyed, and ridges which had lent to the landscape its character have vanished, so that streams have lost their old channels and entered upon wholly different courses.[10]

**Ice-covered Archipelago of Franz Josef Land.** — The islands of Franz Josef Land in the high latitude of 80° and over, with altitudes of 2000 to 4000 feet, and situated as they are on the borders of an open sea, are the most Arctic in their aspect of all the smaller northern land masses. As a consequence, they are with unimportant exceptions completely snow-capped, the snow-ice covering sloping regularly into the sea upon all sides. The Jackson-Harmsworth[11] and Ziegler[12] expeditions, following those of Nordenskiöld, Nansen, the Duke of the Abruzzi, and others, have now supplied us with fairly accurate maps of all islands in the archipelago. One or two of the western islands alone show a narrow strip of low shore land, but with these exceptions all are ice covered save for small projecting peaks or plateau edges near the margins (see Fig. 59). They present, therefore, a unique exception to the law which otherwise obtains, that within the northern hemisphere glacial caps are smaller than the land areas upon which they rest. The appearance of the island covers is here, however, that of *névé* of low density, rather than of compact glacier ice.

Prince Rudolph Island, which was the winter station of the Italian Polar Expedition, is no doubt typical of most islands in the archipelago. This land is described by Duc d' Abruzzi[13] as "completely buried under one immense glacier, which descends to the sea in every direction except at a few points, such as Cape Germania, Cape Säulen, Cape Fligely, Cape Brorok, Cape Habermann, and Cape Auk. At some of these points . . . the coast is almost perpendicular, which prevents the ice from descending to the sea.

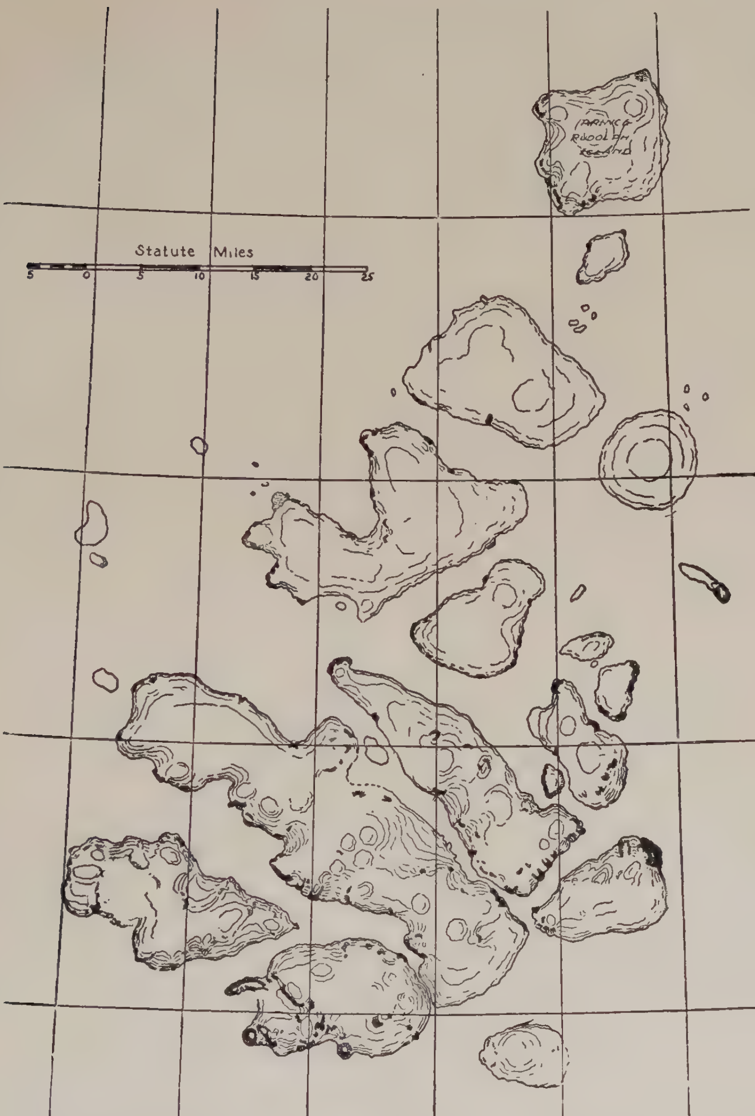


Fig. 59. — Map of the ice-capped islands in the eastern part of the Franz Josef Archipelago (after Fiala).

At others . . . the ice, stopped by a hollow, falls into the sea on each side of the headland, which thus remains uncovered. Moreover, wherever the snow can rest, there are glaciers which end at the sea in an ice cliff, like that formed by the main glacier, so that it can be said that the entire coast, with the exception of a short extent of strand near Teplitz bay, is formed by a vertical ice cliff " (see Fig. 60).

The movement of the ice is so slow that though a line of posts was established for the purpose of measuring during a

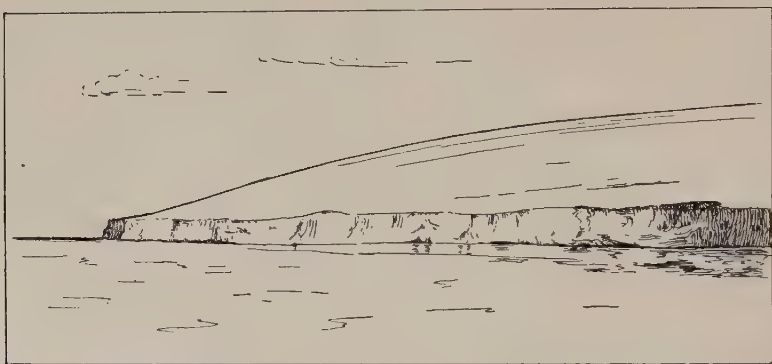

Fig. 60. — Typical ice cliff of the coast of Prince Rudolph Island, Franz Josef Land (after the Duke of the Abruzzi).

period of four months, no movement could be detected. Except near the outermost margin, there were few crevasses, and these were covered by snow. In summer, on days when the temperature was above the freezing point, the snow thawed rapidly so that torrents of water flowed from the glacier to the sea, hollowing out channels, many feet in width.

During the stay of the " Polar Star " near the island, it was noteworthy that thaw and evaporation upon the island exceeded the precipitation. Doubtless because of the slow movement of the ice, no icebergs were seen to form during the entire stay.

**The Smaller Areas of Inland-ice within the Arctic Regions.** — The ice-cap of the Vatna Jökull in Iceland, which is the


Fig. 61. — Map of Nova Zembla, showing the supposed area covered by inland-ice (from Andree's "Handatlas").

largest to which this name has been applied, covers an area of 8500 square kilometers. Ice carapaces, which are better described as inland-ice, since they cover considerable propor-

tions of the interiors of the land areas upon which they rest, occur to the northward of the continent of Europe in Nova Zembla and Spitzbergen, and in the lands to the west of Baffin's Bay, known as Baffin, Ellesmere, and Grinnell lands.


FIG. 62. — Map of Spitzbergen, showing the supposed glacier areas (from Andree's "Handatlas").

Nova Zembla is a long, narrow island, stretching between 70° and 84° of north latitude (see Fig. 61). It is, in reality, two islands separated by a narrow strait near the latitude of 76°. The northern island, which to the north is a plateau attaining an altitude of 1800 feet, is supposed to be in large

part covered by inland-ice, though it has been as yet but little explored.[14]

**The Inland-ice of Spitzbergen.** — The group of islands to which the name Spitzbergen has been applied lies between the parallels of 76° and 81° of north latitude. The surface is generally mountainous, the highest peaks rising to an elevation of about 5000 feet, though the greater number range from 2000 to 4000 feet in altitude. The large northeastern land mass is called North East Land and is covered with inland-ice which was crossed by Nordenskjöld and Palander in

FIG. 63. — Inland-ice of New Friesland as viewed from Hinloopen Strait (after Conway).

1873[15] (see Fig. 62). New Friesland, or the northeastern portion of the main island, is also covered by inland-ice[16] (see Fig. 63). The southwestern margin of this inland-ice was somewhat carefully mapped by Conway and Gregory in 1896,[17] and as this presents some interesting general features, the map is reproduced in part in Fig. 64.

In addition to the lobes which push out upon the crest of the plateau, there is here an expansion laterally beyond the main cap and at lower levels in the form of an apron which is called the Ivory Gate (compare the Frederikshaab Glacier in Fig. 94, p. 171). Surrounding the inland-ice to the westward are small ice-caps resembling the fjelds and braes of Norway, and also true mountain glaciers whose cirques have shaped the mountains into the sharp pinnacles of comb ridges. It is to these sharp peaks that Spitzbergen owes its name.

In the year 1890 Gustav Nordenskjöld made a journey between Horn Sound and Bell Sound on the west coast, and found behind the sharp peaks bordering the coast an ice surface almost without crevasses or nunataks.[18] Upon the north-


Fig. 64. — Map of the southwestern margin of an extension of the inland-ice of New Friesland (after Conway).

west coast no sharp peaks or comb ridges are found, but there is a low plateau with deep, narrow valleys similar to the west coast of Norway, where it reaches the sea near the North Cape. All the rock surfaces are glaciated.

The inland-ice of North East Land reaches the sea upon the southern and eastern coasts, but is surrounded by a hem of land upon the north and west. Over the surface of this ice

Nordenskjöld journeyed in the spring of 1873, finding it to be probably from 2000 to 3000 feet in thickness. Where it reaches the sea on the east coast is a steep and inaccessible cliff of ice, one of the largest in the northern hemisphere.[19] On the northern margin, however, the ice moves out upon a plain with its own upper surface of gentle slope, which except for the crevasses, is not difficult of ascent. From near this northern border good seeing conditions enabled Nordenskjöld to say that the ice mass stretched away to the south and west without any interruption from nunataks, but rising with great uniformity into the great flat dome of its central area. Over this snow surface every puff of wind drove before it a stream of fine snow dust, which insinuated itself into everything and was as troublesome as the sand of a desert.[20]

The upper layer of the glacier was not of ice, but consisted of hard, white, compacted snow which had been smoothed and polished by the abrasion of the wind-driven snow dust. In a depth of four to six feet the surface layer of compact snow passed over into ice, first through a layer of magnificent ice crystals, next to a distinctly granular ice, and finally into a hard, coherent ice mass in which only the numerous cavities filled with compressed air gave evidence of the manner of its formation. When the ice-wall about these cavities is by melting made too weak to sustain the pressure of the air compressed within them, it breaks up with a peculiar crackling sound which in summer is continually to be heard from the pieces of granular ice floating about in the fjords.

"We wandered," says Nordenskjöld, "over a kind of *névé region*, that is to say, over a part of the glacier where the surface is occupied by a layer of snow which does not melt away during summer, whereas in Greenland at the beginning of the month of July the snow upon the surface of the glacier was, on the contrary, already nearly completely melted. No

trace of the glacier lakes, the beautiful and abundant glacier streams, the fine waterfalls and fountains, etc., which occur everywhere on the Greenland inland-ice can be observed here, and the configuration of the surface showed that such forms never occur, or only to a very limited extent. The melting of the snow clearly goes on in Spitzbergen on too inconsiderable a scale for such phenomena to arise."

"The surface of the snow was, as has been already mentioned, quite level, generally hard packed by the storms,

Fig. 65. — Camping place in one of the "canals" upon the surface of the inland-ice of North East Land, Spitzbergen (after Nordenskjöld).

and completely glazed and polished by the stream of snow which even the gentlest breeze of wind carried forward along the ground. This stream of snow, or more correctly of air mixed with snow, had, however, in the absence of a downfall, and provided the wind was not all too violent, only a depth of a few feet. It threw fragile bridges of snow over the crevasses, but did not fill them; formed where there were great precipices, true snow cascades; and filled up in a few minutes

all shallow holes and depressions. Thus, for instance, when we emerged from our tent in the morning, all trace that the snow had been trampled down the evening before had generally disappeared, and the sledges were concealed in a large drift." [21]

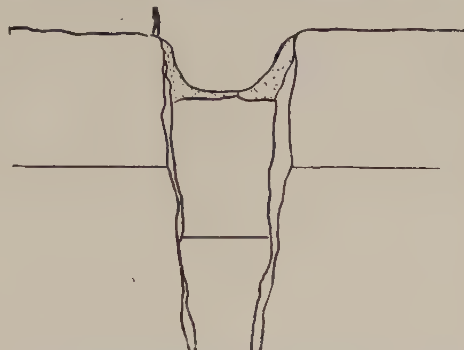

FIG. 66. — Hypothetical cross section of a glacial canal upon the inland-ice of North East Land (after Nordenskjöld).

Of especial note were the great crevasses which ran generally in straight lines for long distances in parallel series, sometimes two intersecting series being observed. More remarkable than these, however, were the so-called "canals," which also for the most part ran parallel to each other, and in some cases were only 100 feet apart. These canals, which were found in the southeastern part of the area near Cape Mohn, were in reality deep, flat-bottomed troughs within the ice, bounded on either side by parallel and rectilinear ice cliffs, and were in places partially filled by the indrifted snow. Stretching for long distances over the snow plain, and set so deeply that they could be entered only where fortuitous drifting of the snow supplied an incline, they were utilized for camping places (see Fig. 65).

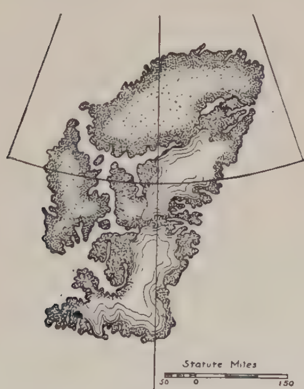


FIG. 67. — Map showing the supposed area of inland-ice upon Grinnell and Ellesmere Lands (from Andree's "Handatlas").

Nordenskjöld has explained these canals as trough faults within the ice, and has assumed that this deformation was

due to changes of volume incidental to extreme temperature range (see Fig. 66). This explanation in temperature changes would leave the absence of such structures in other places wholly unaccounted for, and we venture to believe that a recent trough faulting within the rock basement below the ice, and communicated upward through it, would furnish a more reasonable explanation, particularly in view of our later knowledge of dislocations connected with earthquake disturbances.

Still deeper inbreaks of the ice were encountered within the same region. These, though deeper, were generally of

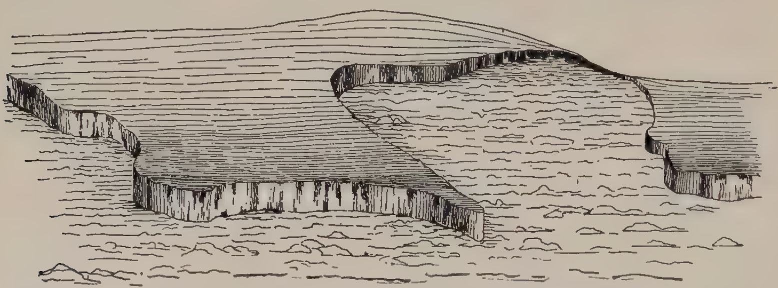

FIG. 68. — View of the "Chinese Wall" surrounding the Agassiz Mer de Glace on Grinnell Land (after Greely).

less extent, and were designated by the sailors of the party "docks" or "glacier docks."

**The Inland-ice of Grinnell, Ellesmere, and Baffin Lands.** — Something has been learned of the inland-ice of Grinnell Land (see Fig. 67) from the report of Lieutenant Lockwood upon his crossing of Grinnell Land in 1883.[22] Of especial interest is his description of the ice front or face as it was observed for long distances in the form of a perpendicular wall which he described under the name "Chinese Wall." Over upland and plain this wall extended with little apparent change in its character. At one place by pacing and sextant angle its height was estimated at 143 feet (see Fig. 68).

The inland-ice of Ellesmere Land (see Fig. 67) has been to

some extent explored along its borders by members of the Sverdrup Expedition.[23] The maps of the margin in the vicinity of Buchanan Bay display much the same characters as


FIG. 69. — Map showing the supposed area of inland-ice upon Baffin Land (from Andree's "Handatlas").

may be observed along the margins of the better-known ice-caps and inland-ice masses of the northern hemisphere.

Of the inland-ice of Baffin Land little is known (see Fig. 69). There are some indications that a small ice-cap exists upon the neighboring island of North Devon.

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[2] W. M. Conway, "An Exploration in 1897 of some of the Glaciers of Spitzbergen," *Geogr. Jour.*, vol. **12**, 1898, pp. 142–147.

[3] It has not in most cases yet been determined to what extent the present nourishment of these glaciers suffices to maintain them, or, per contra, to what extent they are mere waning remnants of larger pre-existing masses. It is, however, known that formerly they were much larger.

[4] H. Hess, "Die Gletscher," 1904, pp. 66, 90–92.

[5] Th. Thoroddsen, "Island, Grundriss der Geographie und Geologie," *Pet. Mitt.* (Ergänzungshefts 152, 153), 1906, V., "Die Gletscher Islands," pp. 163–208.

[6] Hans Spethmann, "Der Nordrand des isländischen Inlandeises Vatnajökull," *Zeitsch. f. Gletscherk.*, vol. **3**, 1909, pp. 36–43.

[7] Carl Sapper, "Bemerkungen über einige südisländische Gletscher," *Zeitsch. f. Gletsch.*, vol. **3**, 1909, pp. 297–305, two maps and three figures. See especially Fig. 3.

[8] Max Ebeling, "Eine Reise durch das isländische Südland," *Zeit. Gesellsch. f. Erdkunde*, Berlin, 1910, pp. 361–382.

[9] R. S. Tarr, "Some phenomena of the glacier margins in the Yakutat Bay Region, Alaska," *Zeit. f. Gletscherk.*, vol. **3**, 1909, pp. 94–96, Fig. 6.

[10] Otto Nordenskjöld, "Die Polarwelt," 1909, pp. 42–43.

[11] F. G. Jackson, "A Thousand Days in the Arctic," 1899, map 5.

[12] Anthony Fiala, "The Ziegler Polar-Expedition of 1803–05," 1907, map C.

[13] "On the 'Polar Star' in the Arctic Sea," vol. **1**, pp. 116–118.

[14] Professor Hanns Höfer, "Graf Welczeks Nordpolar-fahrt im Jahre 1872, III Ueber die Gletscher von Nova Zembla," *Pet. Mitt.*, vol. **21**, 1875, pp. 53–56. See also Commandant Charles Bénard, "Dans l'océan glacial et en Nouvelle-Zemble," Paris, 1910, pp. 1–193.

[15] A. E. Nordenskjöld, "Grönland," map on p. 141.

[16] W. Martin Conway, "An Exploration in 1897 of some of the Glaciers of Spitzbergen," *Geogr. Jour.*, vol. **12**, 1898, pp. 137–158.

[17] Sir Wm. Martin Conway, "The First Crossing of Spitzbergen," London, 1897, pp. 371, 2 maps.

[18] O. Nordenskjöld, *l.c.*, p. 52.

[19] See O. Nordenskjöld, Die Polarwelt, p. 52.

[20] A. E. Nordenskjöld, "Die Schlittenfahrt der schwedischen Expedition im nordöstlichen Theile von Spitzbergen, 24 April–15 Juni 1873," *Pet. Mitt.*, vol. **19**, 1873, pp. 450–453.

[21] Nordenskjöld, l.c., pp. 255–257.

[22] A. W. Greely, "Report on the Proceedings of the United States Expedition to Lady Franklin Bay, Grinnell Land," vol. **1**, especially Appendix No. 86, pp. 274–279, pls. 1–4. See also Salisbury, *Jour. Geol.*, vol. **3**, p. 890.

[23] Otto Sverdrup, "New Land," 2 vols., London, 1904, pp. 496–504.

# CHAPTER VIII

## PHYSIOGRAPHY OF THE CONTINENTAL GLACIER OF GREENLAND

**General Form and Outlines.**—The inland-ice of Greenland, we have now good reason to believe, has the form of a flat dome, the highest surfaces of which lie somewhat to the eastward of the medial line of the continent.[1] This ice dome envelops all but a relatively narrow marginal rim. The marginal ribbon of land is usually from five to twenty-five miles in width, may decrease to nothing, but in two nearly opposite stretches of shore it widens to from sixty to one hundred miles (see Fig. 70).

At the heads of many deep fjords long and narrow marginal tongues pushing out from the central mass reach to below sea level; and within three limited stretches of shore the ice mantle overlaps the borders of the continent and reaches the sea in a broad front. The longest of these begins near the Devil's Thumb on the west coast at about latitude 74′ 30″, and extends with some interruptions for about one hundred and fifty miles along the coast of Melville Bay.[2] Where crossed by Nansen near the parallel of 64°, and hence near the southern margin, and also where traversed by Peary near its northwestern borders, the inland-ice has revealed much the same features. The great central area has never been entered, although Baron Nordenskjöld and Commander

Peary have each passed somewhat within the margin near the latitude of 68°, and Jensen near latitude 63°[3] (see Fig. 70).

In 1893 Garde at the extreme southern end of the con-


Fig. 70. — Map of Greenland, showing the outlines of the inland-ice (from Andree's "Handatlas," but corrected for the northeast shore from data of the Danish expedition of 1908). The routes of the various expeditions on the inland-ice have also been added.

tinent (latitude 61°–62°) penetrated the area of the inland-ice a distance of about sixty-five miles.[4] The route of the expedition and the contours of the surface are given in Fig. 71.[5] The first partially successful attack upon the inland-ice was that of Dr. I. I. Hayes, Commander of the United States Exploring Expedition, which spent the winter of 1860–1861 on Smith Sound in northwestern Greenland. Hayes succeeded in reaching a point seventy miles within the margin of the ice at an elevation of about 5000 feet.[6]

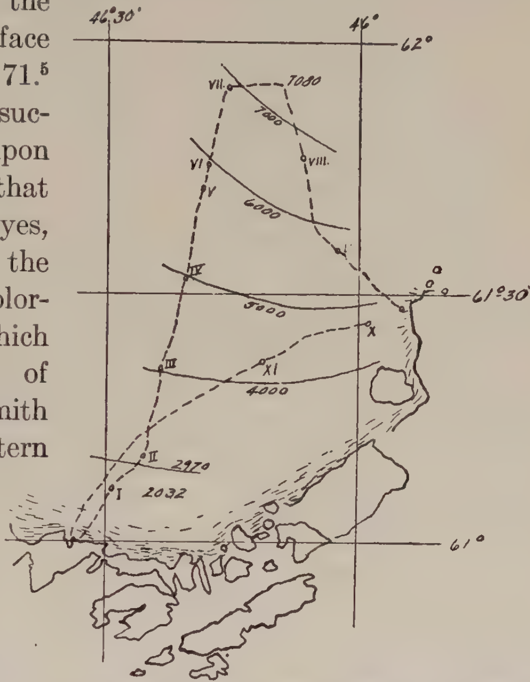


Fig. 71. — Route of Garde across the margin of the inland-ice of South Greenland in 1893 (after Garde).

Recently (1907) Mylius Ericksen met his tragic death in crossing the inland-ice in northeast Greenland, but his results, most fortunately recovered, through the heroism of Bronlund, are not yet published. Yet such is the monotony of the surface thus far revealed, and such the uniformity of conditions encountered, that there is little reason to think future explorations in the interior will disclose anything but a desert of snow, with such small variations from a horizontal surface as are not strikingly apparent to the traveller at any one observing point.

Nansen has laid stress upon the close adherence of the

curve of his section to that of a circle, and has attempted to apply this interpretation to the sections of both Nordenskjöld and Peary made near the latitude of Disco Bay.[7] If the marginal portions of the sections be disregarded, this interpretation is possible for Nansen's own profile, since it is

FIG. 72. — Sketch of the east coast of Greenland near Cape Dan. Shows the inland-ice and the work of marginal mountain glaciers (after Nansen).

in any case very flat; but inasmuch as the margins only were traversed in the other sections, the conclusions drawn from them are likely to be misleading when extended into the unknown interior.

Hess,[8] correcting Nansen's data so as to take account of the curvature of the earth, finds the radius of this circle of the section to be approximately 3700 km. (instead of 10,380 km., as given by Nansen). This radial distance being considerably less than the average for the earth's surface, the curvature of the ice surface where crossed by Nansen is considerably more convex than an average continental section.

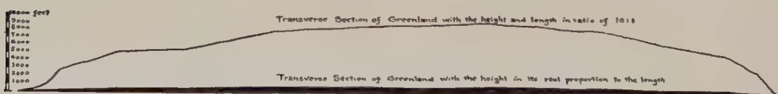


FIG. 73. — The section across the inland-ice of Greenland, near the 64th parallel of latitude in natural proportions and with vertical scale ten times the horizontal (after Nansen).

We are absolutely without knowledge concerning either the thickness of the ice shield or the elevation of the rock basement beneath it, though a height of the snow surface of approximately 9000 feet was reached by Nansen at a point where it could hardly be expected to be a maximum. The snow surface to the north of his section was everywhere ris-

ing, and it is likely that it attains an altitude to the northeastward well above 10,000 feet.

Though doubtless almost flat within its central portions, and only gently sloping outward at distances of from seventy-five to one hundred miles within its margin, the snow surface falls away so abruptly where it approaches its borders as to be often quite difficult of ascent (see Fig. 73).[9] The monotony of the flatly arched central portion of the isblink[10]

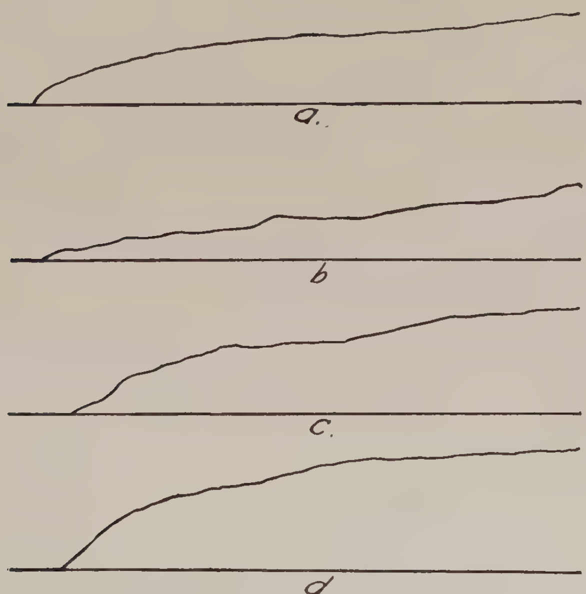


Fig. 74. — Comparison of the several profiles across the margin of the inland-ice: (*a*) at latitude 69½° on the west coast (Peary); (*b*) at latitude 68½° on the west coast (Nordenskjöld); (*c*) at latitude 64° on the west coast (Nansen); and (*d*) at latitude 64½° on the east coast (Nansen).

gives place to wholly different characters as the margins are approached. The ice descends in broad terraces or steps, which have treads of gentle inclination but whose risers are of greater steepness, and this steepness is rapidly accelerated as the margin is neared. In Fig. 74 have been placed together for comparison the profiles of Peary, Nordenskjöld,

and Nansen on the different routes which they travelled toward the interior from the coast.

The margins of the Greenland continent where uncovered by the ice, are generally mountainous, with heights reaching in many cases to between 5000 and 8000 feet on the east shore [11] and between 5000 and 6000 feet on the west shore. The bordering ice-caps within these areas are developed in special perfection on the islands of the archipelago about King Oscars fjord and Kaiser Franz Josef fjord on the east coast near latitude 75° N., as these have been mapped by the Swedish Greenland Expedition of 1899 (see Fig. 75).[12] The

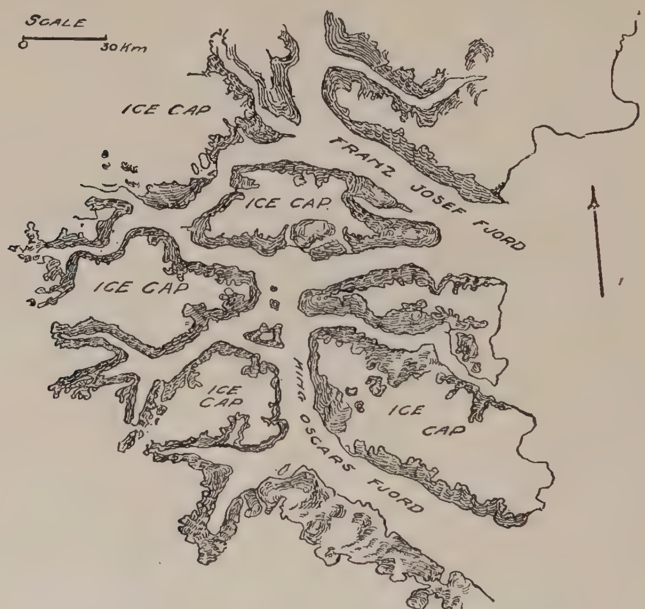


FIG. 75. — Map of the region about King Oscars and Kaiser Franz Josef fjords, Eastern Greenland, showing the areas of the numerous ice-caps (after P. Dusen).

work of mountain glaciers about King Oscars fjord is clearly displayed by Nathorst's photograph reproduced in plate 22 A. Essentially the same features are shown also to the right in Fig. 72 (p. 122).

*A.* Fretted upland carved by mountain glaciers about King Oscar's Fjord, eastern Greenland. The highest points are from 1360 to 1570 metres above the sea (after Nathorst).

*B.* Front of the Bryant glacier tongue showing the vertical wall and stratification of ice. It also shows the absence of rock débris from the upper layers (after Chamberlin).

While we are without absolute knowledge of the relief of the land beneath most of the inland-ice, we know that the mountainous upland of the coast extends well within the ice margins, since the peaks project through the surface as ice-bounded rock islands or *nunataks*. The irregularities of this basement and the submergence and consequent drowning of the valleys to form deep fjords within the marginal zones, largely account for the markedly lobate outlines of the so-called isblink or inland-ice, as well as for the ice-caps and mountain glaciers, which, originating in the outlying plateaus and mountains, form a fringe about the central ice mass.

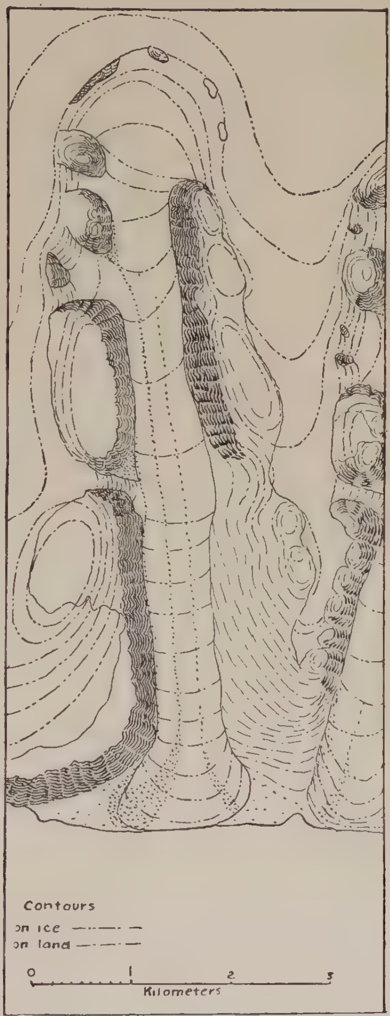

FIG. 76. — Map of a glacier tongue, which extends from the inland-ice down the Umanak fjord (after von Drygalski).

It has been shown to be characteristic of the ice-caps and smaller inland-ice areas of the Arctic region outside of Greenland, that their lobate margins are in part accounted for by extensions of the cap upon the plateau between intersecting valleys or fjords, as well as by extensions down these valleys. These latter

extensions of the ice-sheets are, however, much the narrower. Identically the same features are found to characterize the Greenland inland-ice as well. The manner in which this occurs in Greenland has been well brought out in a map and section by Helland [13] of the Kangerdlugsuak fjord and glacier, but even better by recent maps of the Petermann fjord by Peary (Fig. 81, p. 133) and the Umanak fjord by von Drygalski [14] (see Fig. 76). The manner in which the ice sometimes descends from the higher levels over the steep walls of the fjords has been strikingly brought out in a photograph of the Fœtal glacier (see Fig. 77).[15]

Fig. 77. — Tongues of ice descending from the Fœtal glacier, McCormick Bay (after Peary).

As already stated, within one limited stretch upon the west coast the ice mantle overlaps the borders of the continent and reaches the sea in a broad front. This stretch of coast begins near the Devil's Thumb at about latitude

74° 30′ and extends, with some interruption, for about 150 miles along the coast of Melville bay.[16] On the northeast coast the recent explorations of the Danes indicate that there are two stretches of 20 and 60 miles, respectively, within which the ice in like manner reaches the sea. These occur on Jökull bay and on the north shore of the North East Foreland (see Fig. 78).[17]

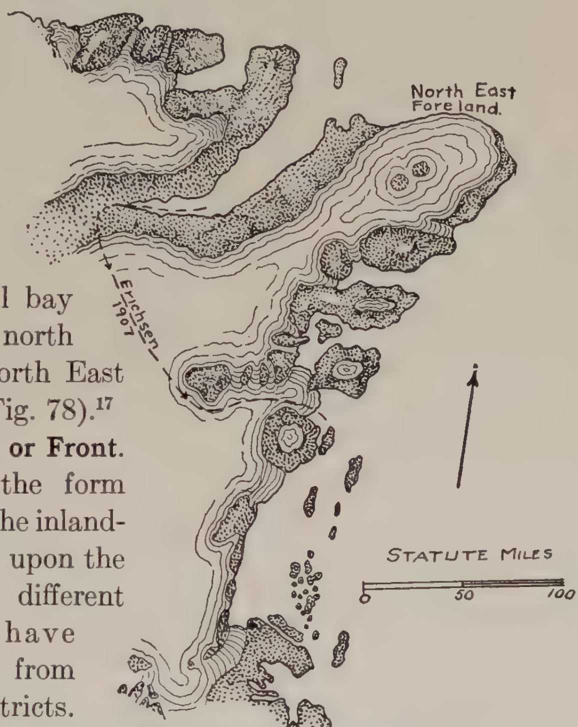

Fig. 78. — Map of the Greenland shore in the vicinity of the North East Foreland (after Trolle).

**The Ice Face or Front.** — Concerning the form of the front of the inland-ice where it lies upon the land, widely different descriptions have been furnished from different districts. It is necessary to remember that the continent of Greenland stretches northward through nearly 24° of latitude, and after due regard is had to this consideration, the differences in configuration may, perhaps, be found to be but expressions of climatic variation. Those who have studied the land margin of the isblink in North Greenland, all call attention to the precipitous and generally vertical wall which forms the ice face (see plate 22 B). As a result of shearing and overthrusting movements within the ice near

its margin, as well as to the effect of greater melting about the rock fragments imbedded in the lower layers of the ice, the face sometimes even overhangs in a massive ice cornice at the summit of the wall (see plate 23 A).[18]

That to this remarkable steepness of the ice face as observed north of Cape York there are exceptions, has been mentioned by both Chamberlin and Salisbury, but Peary has also emphasized the vertical face as a widely characteristic feature of North Greenland. The recent Danish Expedition to the northeast coast of Greenland has likewise furnished examples of such vertical walls. An instance where the ice face appears as a beautifully jointed surface somewhat resembling the rectangular joint walls in the quarry faces of certain compact limestones, is reproduced from the report of the expedition in plate 23 B.[19]

Attention has already been called to the precipitous front, the so-called "Chinese Wall," which Lieutenant Lockwood found to form the land face of the inland-ice of Ellesmere Land — a face which was followed up and down over irregularities of the land surface, and whose height in one place was roughly measured as 143 feet (see Fig. 68, p. 116).

From central and southern Greenland, on the other hand, we hear little of such ice cliffs as have been described, and Tarr in studies about the margin of the Cornell extension of the isblink[20] has shown that here the vertical face is the exception.[21] The normal sloping face as there seen is represented in plate 24 A. In following the ice face for fifteen miles, its slopes were here found to be sufficiently moderate to permit of frequent and easy ascent and descent. Inasmuch as these sloping forms are characteristic of the ice front in the warmer zones, and further correspond to that generally characteristic of mountain glaciers in lower latitudes, it seems likely that its occurrence in Greenland is limited to districts where surface ablation plays a larger rôle.

*A.* Portion of the southeast face of the Tuktoo glacier tongue showing the projection of the upper layers apparently as a result of overthrust (after Chamberlin).

*B.* Ice-face at eastern margin of the inland-ice of Greenland in latitude 77° 30′ N. (after Trolle).

In Northeast Greenland (lat. 77°–82°), according to the Danes, "the frontier of the inland-ice is in some places quite steep, in other places you might have mounted the inland-ice without knowing it."

**Features within the Marginal Zone.** — The larger terraces upon the ice-slope, Nansen has ascribed to peculiarities of the rock floor on which the ice rests. Where the slopes become still more accelerated toward the margin of the ice, deep crevasses appear upon these steps running parallel to their extension, and hence parallel to the margins of the ice. Nansen found, however, that such crevasses were restricted to the outer seven or eight miles on the eastern side of his section, and to the outer twenty-five miles on its western margin. Peary in his reconnoissance across the ice border

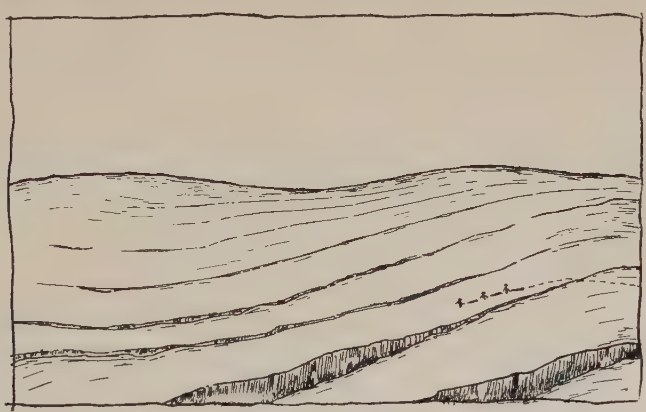

Fig. 79. — A series of parallel crevasses on the inland-ice of South Greenland (after Garde).

in latitude $69\frac{1}{2}°$, saw such crevasses while they were opening and the surface snow was sinking into the cleft thus formed. The visible opening of the cleft was accompanied by peculiar muffled reports which rumbled away beneath the crust in every direction.[22]

In addition to the crevasses which develop transversely

to the main direction of ice movement, and which are with much probability located over " steps " in the rock floor, there are evidently others which fall in a somewhat different category. The series of parallel crevasses resembling ravines which are figured by Garde [23] and take their course over the gently swelling surface of the ice (see Fig. 79) bear more resemblance to the longitudinal crevasses which one finds between the nunataks upon the surface of the plateau glaciers of Norway, as, for example, the Hardanger-jökull. Of very considerable interest also are the rectangular networks of crevasses which are described by the same author from near the margin of the ice (see Fig. 80).[24]

FIG. 80. — Rectangular network of crevasses on the surface of the inland-ice near its margin in South Greenland (after Garde).

This network recalls the rectangular system of crevasses which was observed by the German Expedition on the inland-ice of Kaiser Wilhelm Land (see Fig. 129).

Of the terraced slope and its fading into the plateau above Peary says: —

The surface of the "ice-blink" near the margin is a succession of rounded hummocks, steepest and highest on their landward sides, which are sometimes precipitous. Farther in these hummocks

*A.* Normal slope of the inland-ice at the land margin near the Cornell tongue (after Tarr).

*B.* Hummocky moraine on the margin of the Cornell glacier tongue (after Tarr).

merge into long, flat swells, which in turn decrease in height towards the interior, until at last a flat gently rising plain is revealed which doubtless becomes ultimately level.[25]

In sketching the general form of the Greenland continental glacier, it has been stated that the highest portion of the shield lies to the eastward of the medial line of the continent. This is shown by Nansen's section, and is emphasized by Peary, who says: —

> That the crest of the Greenland continental ice divide is east of the country's median line there can be no doubt.[26]

By von Drygalski [27] this lack of symmetry of the ice mass has been ascribed to excessive nourishment upon the east, whereas the losses from melting and from the discharge of bergs occur mainly upon the west. The mountains of the east are, he states, completely surrounded by ice so that peaks alone project, while the mountains of the west stand isolated from the ice. In attempting to make the eccentric position of the boss in the ice shield depend upon the configuration of the underlying rock surface, von Drygalski has been less convincing, for we know that the Scandinavian continental glacier of Pleistocene times moved northwestward from the highest surface of the ice-shield up the grade of the rock floor, and pushed out through portals in the mountain barrier which lies along the common boundary of Sweden and Norway.

We shall see, moreover, that the nourishment of the Greenland ice is by a different process than that which he has assumed. Still there would appear to be a clear parallel between the marginal terraces of the inland-ice with their crevassed steep surfaces, and the plateaus and ice-falls which alternate upon the slopes of every mountain glacier which descends rapidly in its valley.

Superimposed upon the flats of the larger ice terraces, there are undulations of a secondary order of magnitude, and these Nansen ascribed to the drifting of snow by the wind. To the important action of wind in moulding the surface of the inland-ice we shall refer again. There are in addition many other irregularities of the surface due to differential melting, and while of very great interest, their consideration may profitably be deferred until the meteorological conditions of the region have been discussed. There are, however, other features which like the broader terraces are clearly independent of meteorological conditions, and which are, therefore, best considered in this connection.

**Dimples or Basins of Exudation above the Marginal Tongues.** — Seen from the sea in Melville bay on the northwest coast, the inland-ice offers special advantages for observing its contours in sections parallel to its front, that is to say, in front elevation. Here only upon the west coast the ice extends beyond the borders of the land and is cut back by the sea to form cliffs. These ice cliffs are interrupted by rocky promontories which are surrounded on all sides but the front by ice, and hence in reality the cliff furnishes us with sections through nunataks and inland-ice alike. Says Chamberlin: [28] —

> Only a few of the promontories of the coast rise high enough to be projected across this sky-line and interrupt the otherwise continuous stretch of the glacial horizon. The ice does not meet the sky in a simple straight line. It undulates gently, indicating some notable departure of the upper surface of the ice tract from a plane. As the ice-field slopes down from the interior to the border of the bay, it takes on a still more pronounced undulatory surface. It is not unlike some of our gracefully rolling prairies as they descend from uplands to valleys, when near their middle-life development.

The two 1200-mile sledge journeys of Peary in the years 1891–1892 and 1893–1895 across the northern margin of the

"Great Ice" of Greenland, have added much to our knowledge of the physiography of the inland-ice. These journeys were made on nearly parallel lines at different distances from the ice border, and so, if studied in relation to each other, they display to advantage the configuration of the ice surface near its margin (see Fig. 81). The routes were for the most part nearly straight and ran at nearly uniform elevations which ranged from 5000 to 8000 feet above the sea.[29] In the sections nearest the coast, however, the route at first ascended a gentle rise to a flatly domed crest upon the ice, only to descend subsequently into a broad swale of the surface, the bottom of which might be described as a plain, and which was continued in the direction of the coast by a tongue-like extension of


Fig. 81. — Map showing routes of sledge journeys in North Greenland in their relation to the margin of the ice (after Peary).

the ice, such as the tongue in Petermann fjord between Hall Land and Washington Land (Fig. 81). On the farther side of this basin-like depression, the surface again rose until another domed crest had been reached, after which a descent began into a swale similar to the first. On the return journey by keeping farther from the ice margin these elongated dimples upon the ice surface were avoided. The broad domed surfaces which separate the dimples clearly lie over the land ridges between the valleys down which the glacier tongues descend toward the sea.

Peary has referred to these dimples on the surface of the inland-ice as "basins of exudation," and has compared the cross profile in its ups and downs to that of a railroad located along the foot-hills of a mountain system.[30] In his earlier reconnaissance of the isblink from near Disco Bay, Peary describes such a dimple above the Jakobshavn ice tongue "stretching eastward into the 'ice-blink,' like a great bay," as a *feeder basin*.[31] The exact form of such dimples upon the ice surface is well brought out in von Drygalski's map of the Asakak glacier tongue on the Umanak fjord (see Fig. 76, p. 125).[32]

We may easily account for the existence of these dimples by drawing a parallel from the behavior of water as it is being discharged from a lake through a narrow and steeply inclined channel. Under these circumstances the surface is depressed through the indrawing of the water on all sides to supply the demands of the outflowing current. That within the upper portions of the glacier tongues of the Greenland isblink the ice flows with a quite extraordinary velocity has long been known. Values as high as 100 feet per day have been determined upon the Upernavik glacier.[33] By more accurate methods, von Drygalski has obtained on one of the ice tongues which descends to a fjord a rate of about 18 meters or 59 feet in twenty-four hours.[34] Upon the in-

land-ice some distance back from the head of the fjord, on the other hand, a rate was measured of only one to two centimeters per day.

**Scape Colks and Surface Moraines.** — The velocities of ice movement which obtain within and about the heads of the glacial outlets are, there is thus every reason to believe, as different as possible from the ordinary general outward movement of the inland-ice. Within this marginal zone areas of exceptional velocity of the inland-ice are likely to be found wherever its progress is interfered with by the projecting nunataks. Just as jetties by constricting the channels greatly accelerate the velocity of stream flow within those channels, so here within the space between neighboring nunataks a local high rate of flow in the ice is developed. An inevitable and quite important consequence of this constriction was long ago pointed out by Suess and illustrated by the area between Dalager's nunataks near the southwestern border of the isblink.[35] Here again the conduct of water which is being discharged through narrow outlets has supplied both the illustration and the explanation. In the regulation of the flow of the Danube below Vienna, the river was partially closed by a dam, the Neu-Haufen dike, and the floor in the channel below the dike was paved with heavy stone blocks. The effect of thus narrowing the channel of the river was to raise the level of the water above the dike by almost a metre, and under this increased head the current tore out the heavy stone paving of the floor of the channel and dug a depression above as well as below the outlet. This excavation by the current represented a hole dug to a depth of about fifteen metres. The blocks which had been torn out from the pavement were left in a crescent-shaped border to the depression upon its downstream side (see Fig. 82 *a*).

The position of a surface moraine which stretches in a

sweeping arc from the lower edge of one of Dalager's nunataks to a similar point upon its neighbor, indicates a complete parallel between the motion of the ice and the water at the Neu-Haufen dyke, the rock débris of the deeper ice

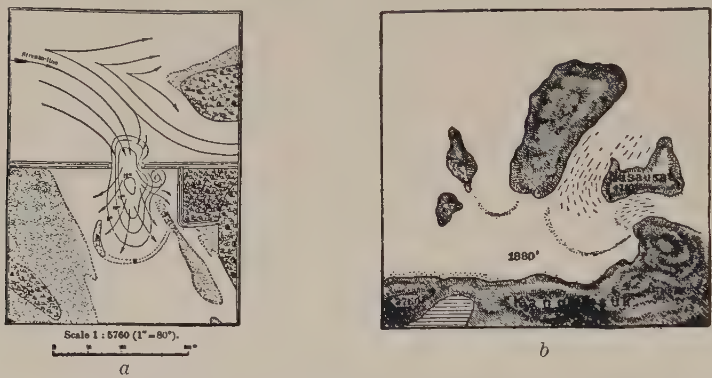


FIG. 82. — *a*, Closure of the Neu-Haufen dyke, Schüttau in the regulation of the Danube below Vienna (after Taussig) ; *b*, Scape colks near Dalager's Nunataks (after Jensen and Kornerup).

layers being here brought up to the surface. Study of the Scandinavian inland-ice of late Pleistocene times throws additional light upon the nature of this process. Flowing from a central boss near the head of the Gulf of Bothnia, the ice pushed westward and escaped through narrow portals in the escarpment which now follows the international boundary of Sweden and Norway. This constriction of its current has been appealed to by Suess to account for the interesting glint lakes which to-day lie across this barrier and extend both above and below the former outlets for the ice.[36] Lakes which have this origin he has described under the term "scape colks." Perhaps if examined more carefully, we should find that the bringing up of the englacial débris to the surface of the ice, is only partially due to the inertia of motion in the ice. With the more rapid flow of the ice within the constricted portion, the basic layers, shod as they are with rock fragments, accomplish excessive abrasion upon the rock

bed. This is in accord with Penck's law of adjusted cross-sections in glacial erosion. Where the ice channel broadens below the nunataks, the abrasion again becomes normal so that a wall develops at this place in the course of the stream.

Here, therefore, a new process comes into play due to the peculiar properties of the plastic ice, a process which has been illustrated in the formation of drumlins beneath former continental glaciers, and has been given an experimental verification. Case has shown that paraffin mixed with proper proportions of refined petroleum, and maintained at suitable temperatures, can be forced by means of plungers[37] through narrow boxes open at both ends. It was shown in the experiments that an obstruction interposed at the bottom and in the path of the moving paraffin, forced the bottom layers upward, and this upward movement continued beyond the position of the obstruction. The experiments of Hess[38] give results which are consistent with those of Case. Hess employed in his experiments parallel wax disks of alternating red and white colors, and these were forced under hydraulic pressure through a small opening. It was found that the layers turn up to the surface in this " model glacier " apparently as a result of the friction upon the bottom, and at only moderate distances from the opening where the energy of the active moving substance pressing from the rear has to some extent been dissipated.

In Chamberlin's studies of certain Greenland glaciers, he was permitted to observe the effect upon the motion of the glacier of a low prominence in its bed. These observations are confirmatory of the experiments described.[39]

The swirl colks or eddies which Suess has suggested as occurring below nunataks, in order to account for certain lakes in Norway, seem to be much less clear, and it is a little difficult to assume an eddy in the ice which is in any way comparable to the eddies of water.

**Marginal Moraines.** — Inasmuch as the rock appears above the surface of the ice of the Greenland continental glacier only in the vicinity of its margins, and here only as small islands or nunataks, the rock débris carried by the Greenland ice must be derived almost solely from its basement. As described in detail by Chamberlin, it is the lower 100 feet of ice to which englacial débris is largely restricted.[40] Medial moraines, if the term may be properly applied to those ridges of rock débris which upon the surface of the ice go out from the lower angles of nunataks, have been frequently described by Nansen and others. They seem to differ but little from certain of the medial moraines which have been described in connection with the larger mountain glaciers.

Nansen has mentioned heavy terminal moraines in the Austmann Valley, where he came down from the inland-ice after crossing the continent. The material of these moraines consisted mainly of rounded and polished rock fragments, and is obviously englacial material.[41] Along the land margin of the Cornell ice tongue Tarr found a nearly continuous morainic ridge parallel to the ice front. This ridge usually rests at the base of the ice foot, and is sometimes a part of this foot, wherever débris has accumulated and protected the ice beneath from the warmth of the sun. Such an accumulation causes this part of the glacier to rise as a ridge. In other cases the ridge is, however, separated from the ice margin, and sometimes there are several parallel ridges from which the ice front has successively withdrawn [42] (see plate 24 B).

According to von Drygalski the marginal moraines of the Greenland ice sheet, as regards their occurrence, form, and composition, are in every way like those remaining in Northern Europe from the time of the Pleistocene glaciation, and this is true of those which run along the present border

of the inland-ice as well as of those still mightier ancient moraines which follow at certain distances.[43] These moraines are generally closely packed blocks with relatively slight admixture of finer material. They are the largest where the

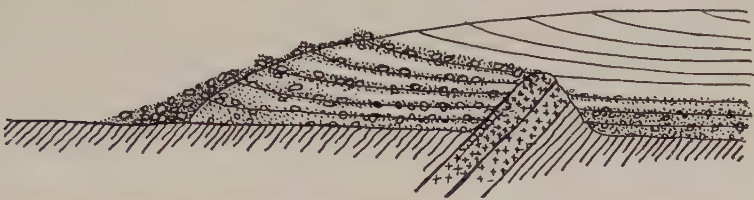

FIG. 83. — Diagram to show the effect of a basal obstruction in the path of the ice near its margin (after Chamberlin).

ice border enters the plains, or pushes out upon a gentle slope, and they are smallest where the ice passes steep rocky angles.

It is worthy of note that the marginal moraines of Greenland become locally so compact and resistant that they

FIG. 84. — Surface marginal moraine of the inland-ice of Greenland (after Chamberlin).

oppose a firm obstruction to the ice movement. Then the ice pushes out laterally into the marginal lakes which develop there or pushes up upon the moraines. It thus comes to

arrange its layers parallel to the slope of the morainic surface or, in other words, so that they dip toward the ice.[44]

Another type of marginal moraine which was mentioned by Mohn and Nansen from South Greenland, and later fully described by Chamberlin from North Greenland, is explained by the upturning effect of obstructions in the bed, and by the shearing and overthrusting movements which are found to exist in inland-ice near its margin[45] (see Figs. 83 and 84). This process has much in common with that which we have already described in connection with scape colks.

**Fluvio-glacial Deposits.** — Where studied by Chamberlin near Inglefield gulf, there appears to be little or no gushing of water from beneath the inland-ice. Small streamlets only appeared beneath the ice border, bringing gravel and sand which they distributed among the coarser morainic material. So far as land has been recently uncovered by the ice in North Greenland, and so far as differentiated from the topography of the underlying rock, it was found to be nearly plane. So far as known, no eskers have been observed about the border of the inland-ice of Greenland, and only a few irregular kames near Olrik's bay.[46]

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[6] I. I. Hayes, "The open polar sea," London, 1867, p. 72.

[7] H. Mohn und Fridtjof Nansen, "Wissenschaftlichen Ergebnisse von Dr. F. Nansens Durchquerung von Grönland, 1888," *Pet. Mitt.*, Ergänzungsh., vol. **105**, 1892, pp. 1–111, 6 pls., 10 figs. Especially Plate 5.

[8] "Die Gletscher," pp. 105–106.

[9] R. E. Peary, "A Reconnoissance of the Greenland Inland-ice," *Jour. Am. Geogr. Soc.*, vol. **19**, 1887, pp. 261–289.

[10] "Iceblink," which has been suggested by some writers, is a term gen-

erally applied among navigators to describe the appearance of ice on the horizon, and is contrasted with "land blink," which describes the peculiar loom of the land. In order to apply the term to the inland-ice without confusion, it is, therefore, better to retain the Danish form of the word.

[11] Petermann Peak near Franz Josef fjord on the east coast, which, according to Nansen, has an estimated height of 11,000–14,000 feet, has recently been shown to be not more than half that height (A. G. Nathorst, *Pet. Mitt.*, vol. **45**, 1899, p. 242).

[12] A. G. Nathorst, "Den svenska expeditionen till nordöstra Grönland," 1899, *Ymer*, vol. **20**, 1900, map 11.

[13] A. Helland, "On the Ice Fjords of North Greenland and on the Formation of Fjords, Lakes, and Cirques in Norway and Greenland," *Quart. Jour. Geol. Soc.*, vol. **33**, 1877, pp. 142–176.

[14] E. von Drygalski, "Grönland-Expedition," vol. **1**, 1897, Map 7.

[15] R. E. Peary, "Journey in North Greenland," *Geogr. Jour.*, vol. **11**, 1898, pp. 213–240.

[16] T. C. Chamberlin, "Glacial Studies in Greenland, III.," *Jour. Geol.*, vol. **3**, 1895, p. 61.

[17] Lieut. A. Trolle, "The Danish Northeast Greenland Expedition," *Scot. Geogr. Mag.*, vol. **25**, 1909, pp. 57–70, map and illustrations.

[18] Chamberlin, *Jour. Geol.*, vol. **3**, 1895, p. 566. Salisbury, *ibid.*, vol. **4**, 1896, p. 778.

[19] Gunnar Andersson, "Danmarks expeditionen till Grönlands nordostkust," *Ymer*, vol. **28**, 1908, pp. 225–239, maps and 7 figures.

[20] To the south of the upper Nugsuak Peninsula in latitude 70° 10′ N.

[21] R. S. Tarr, "The Margin of the Cornell Glacier," *Am. Geologist*, vol. **20**, 1897, pp. 139–156, pls. 6–12.

[22] *Jour. Am. Geogr. Soc.*, vol. **19**, 1887, p. 277.

[23] Garde, l.c., pl. IV. See also J. A. D. Jensen, "Expeditionen till Syd-Grönland, 1878," *Meddelelser om Grönland*, heft **1**, pl. ii.

[24] Garde, l.c., pl. V.

[25] *Geogr. Jour.*, vol. **11**, 1898, pp. 217, 218.

[26] *Geogr. Jour.*, *l.c.*, p. 232.

[27] E. von Drygalski, "Die Eisbewegung, ihre physikalischen Ursachen und ihre geographischen Wirkungen," *Pet. Mitt.*, vol. **44**, 1898, pp. 55–64.

[28] "Glacial Studies in Greenland, III.," *Jour. Geol.*, vol. **3**, 1895, p. 63.

[29] *Geogr. Jour.*, vol. **11**, 1898, p. 215. See also his map, *Bull. Am. Geogr. Soc.*, vol. **35**, 1903, p. 496.

[30] *Geogr. Jour.*, vol. **11**, p. 232.

[31] *Jour. Am. Geogr. Soc.*, vol. **19**, 1887, p. 269.

[32] "Grönland-Expedition," *l.c.*, map 7.

[33] Lieut. C. Ryder in 1886. Helland on a glacier of the Jakobshavnfjord found a rate of 64 feet daily.

[34] E. von Drygalski, "Die Bewegung des antarktischen Inlandeises," *Zeitsch. f. Gletscherk*, vol. **1**, 1906–7, pp. 61–65.

[35] Ed. Suess, "Face of the Earth," vol. **2**, 1888 (translation, 1906), pp. 342–344.

[36] Suess, *l.c.*, pp. 337–346.

[37] E. C. Case, "Experiments in Ice Motion," *Jour. Geol.*, vol. **3**, 1895, pp. 918–934.

[38] "Die Gletscher," 1904, p. 171, fig. 28.

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[43] "Grönland Expedition," *l.c.*

[44] von Drygalski, *l.c.*, p. 529.

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# CHAPTER IX

## NOURISHMENT OF THE GREENLAND INLAND-ICE

**Few and Inexact Data.** — The problems involving the gains and the losses of the inland-ice of Greenland require for their satisfactory solution a much larger body of exact data than we now possess. Barring a few scattered and not always exact or reliable observations, we are practically without knowledge of the amount or the variations of atmospheric pressure, or of snowfall away from the coastal areas of the continent. Even within these marginal zones, the losses from ablation and through the calving of bergs, have been estimated by crude methods only. Again, the great height of the ice surface within the central plateau, and the lack of any knowledge of the elevation of the land surface in those regions, has raised questions concerning the conditions of flow and of fusion upon the bottom which will probably long remain subjects of controversy.

An international coöperative undertaking with one or more stations established in the interior at points where altitude has been determined by other than barometric methods, and with coast stations maintained contemporaneously and for a period of at least a year, particularly if they could be supplemented by balloon or kite observations, would yield results of the very greatest importance.[1] The Greenland ice having shrunk greatly since the Pleis-

tocene period, it is almost certain that its alimentation to-day does not equal the losses which it suffers along its margins — which in but slightly altered form applies to the Antarctic continental glacier as well.

**Snowfall in the Interior of Greenland.** — Almost the only data upon this subject are derived from a rough section of the surface layers of snow, as this was determined by Nansen with the use of a staff near the highest point in his journey across the inland-ice along the 64th parallel. At elevations in excess of 2270 meters Nansen found the surface snow "soft" and freshly fallen, but of dustlike fineness. Beneath the surface layer, a few inches in thickness only, there was a crust less than an inch in thickness which was ascribed to the slight melting of the surface in midsummer,[2] and below this crust other layers of the fine "frost snow" more and more compact in the lower portions, but reaching a thickness of fifteen inches or thereabouts before another crust and layer was encountered.[3] Other sections made in like manner, by pushing down a staff, revealed similar stratification of the surface snow with individual layers never exceeding in thickness a few feet. From these observations Nansen has drawn the conclusion that the layers of his sections correspond to seasonal snowfalls, the thin crust upon the surface of each being due to surface melting in the few warm days of midsummer. He cites Nordenskjöld as believing that the moist winds which reach the continent of Greenland deposit most of their moisture near the margin.[4]

The sky during almost the entire time of the journey is described by Nansen as so nearly clear that the sun could be seen, and there were few days in which the sky was completely overcast. Even when snow was falling, which often happened, the falling snow was not thick enough to prevent the sun showing through. This clearly indicates that the snow falls from layers of air very near the snow surface

below. The particles which fell were always fine, like frozen mist — what in certain parts of Norway is known as "frost snow"; that is, snow which falls without the moisture first passing through the cloud stage.[5]

The air temperatures, even in August and September, when the crossing was made, were on the highest levels seldom much above the zero of the Fahrenheit scale, and at night they sank by over 40° F. (in one case to − 50° F.).

Peary, while on the inland-ice in North Greenland in the month of March, 1894, registered on his thermograph a temperature of − 66° F., and several of his dogs were frozen as they slept.[6] The high altitudes and the general absence of thick clouds over the inland-ice permit rapid radiation, so that cold snow wastes and hot sand deserts have in common the property of wide diurnal ranges of temperature. The poverty of the air over the inland-ice in its content of carbon dioxide, as shown by the analysis of samples collected by Nansen, must greatly facilitate this daily temperature change.[7]

From studies in the Antarctic it is now known that most of the snow falls there in the summer season, and that little, if any, moisture can reach the interior from surface winds. The same is probably true also of the interior of Greenland.

Though the absolute humidity of the air upon the ice plateau of Greenland is always low, the relative humidity is large, and never below 73 per cent of saturation in the levels above 1000 metres. Evaporation occurs chiefly when the sun is relatively high, and when the air is again chilled, the abstracted moisture is returned to the surface in the form of the almost daily snow mists or frost snow. The observations went to show that only in the warmest days of summer do the sun's rays succeed in melting a very thin surface layer of the snow. Of the thirty days that Nansen's party was at altitudes in excess of 1000 metres, on

only six is a definite snowfall reported. Within the interior of Greenland it appears that *no snow whatever is permanently lost from the surface by melting.*[8]

While the relative humidity of the air over the central plateau is so high, the absolute humidity is extremely low, being measured from 1.4 mm. to 4 mm., though generally much below the maximum value. The average absolute humidity was 2.5 mm., while the average relative humidity was 92 per cent.[9]

It has been claimed by von Drygalski that the eastern portion of the Greenland ice sheet is a great nourishing region, while the western slope, on the other hand, is the locus of excessive melting and discharge. In support of this view he adduces chiefly the admitted lack of symmetry of the ice mass.[10] So far as alimentation is concerned, the view does not seem to be as yet supported by any observations, and it can hardly be regarded as a tenable hypothesis.

**The Circulation of Air over the Isblink.** — No exact data upon atmospheric pressures are as yet available, except from stations near the sea level, mainly along the western and northern coasts. Until stations have been maintained for a more or less protracted period within the interior of Greenland, none can be expected. None the less, upon the basis of the observed winds in those portions of Greenland which have been traversed, it may be safely asserted that a fixed area of high atmospheric pressure is centered over the Greenland isblink, and that the cold surface of this mass of ice is directly responsible for its location there. Nansen, as early as 1890, announced this fact, having observed "that the winds which prevail on the coasts have an especial tendency to blow outwards at all points."[11] After many years of experience in different portions of Greenland, Peary stated the law of air circulation above the continent in clear and forceful language:[12] —

Except during atmospheric disturbances of exceptional magnitude, which cause storms to sweep across the country against all ordinary rules, the direction of the wind of the "Great Ice" of Greenland is invariably radial from the centre outward, normal to the nearest part of the coast-land ribbon. So steady is this wind and so closely does it adhere to this normal course, that I can liken it only to the flow of a sheet of water descending the slopes from the central interior to the coast. The direction of the nearest land is always easily determinable in this way. The neighborhood of great fjords is always indicated by a change in the wind's direction; and the crossing of a divide, by an area of calm or variable winds, followed by winds in the opposite direction, independent of any indications of the barometer.

Except for light sea breezes blowing on to the land in February, the Danish Northeast Greenland expedition found "the wind was constantly from the northwest, this being the result of the high pressure of air which is found over the inland ice."[13]

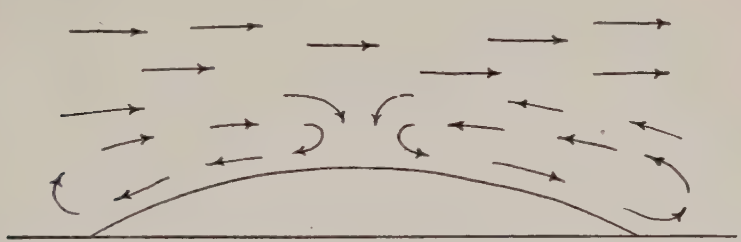

Fig. 85. — Diagram to illustrate the air circulation over the isblink of Greenland.

These conditions of circulation are schematically represented in Fig. 85. In March, 1894, Peary encountered on the north slope of the inland-ice a series of blizzards before unprecedented in Arctic work, one lasting for three days, during which for a period of 34 hours the average wind velocity, as recorded by anemometer, was 48 miles per hour. Viewed in the light of the violent southerly blizzards which Shackelton found to prevail upon the ice plateau in the Antarctic, these winds must be considered as belonging to

the same Greenland or isblink system which has been described as of such general prevalence.

After comparing the meteorological data from his journey with contemporaneous observations on the shores of Baffin's Bay, Nansen believed that he was able to make out faintly the influence of general cyclonic movements. He says:[14]—

> The plateau seems to be too high and the air too cold to allow depressions or storm centres to pass across, though, nevertheless, our observations show that in several instances the depressions of Baffin's Bay, Davis' Strait, and Denmark's Strait, can make themselves felt in the interior.

This, it must be remembered, was in the narrow southern extension of the continent and essentially marginal to the main ice mass. Commenting upon Peary's conclusions above quoted, Chamberlin[15] ascribes the wind which flows downward and outward from the isblink to a notable increase of its specific gravity through contact with and consequent cooling by the snow surface.[16]

It is perhaps well to here allude to the conditions under which heat is added to or abstracted from fluid masses, whether they be liquid or gaseous. Communication is by contact, and distribution by the process known as convection — adjustments of position due to changes in specific gravity resulting from change of temperature. These convection currents must be started either by rendering the upper layers heavier, or the lower layers lighter, than they were when in equilibrium. No distributing convection currents can be set up by heating (making lighter) at the top, or by cooling (making heavier) at the bottom; and so long as confined, no motions of any kind can thus be initiated. Water may be boiled in the upper layers within a test-tube, or frozen in the lower layers, without disturbing the conditions of equilibrium.

Now it is at the bottom that the air above the isblink is cooled by contact; and it is due to the peculiar shield-like form of this ice mass that the heavier cooled bottom layer is able to slide off radially as would a film of oil from a model of similar form. The centrifugal nature of this motion tends to produce a vacuum above the central area of the ice mass, and air must be drawn down from the upper layers of the atmosphere in order to supply the void. It is here that is located the "eye" of the anticyclone.

**Foehn Winds within the Coastal Belt.** — The sliding down of masses of heavy air upon the snow surface of the Greenland ice must bring about adiabatic heating of the air and a consequent elevation of the dew point. The increase of temperature being about 1° C. for every 100 metres of descent, a rise of temperature of as much as 20° C. or 36° F. will result in a descent from the summit of the plateau, assuming this to have an elevation of 10,000 feet. Some reduction in the amount of this change of temperature will, of course, result from the contact of the air with the cold snow surface during its descent, this modification being obviously dependent upon the velocity of the current. The warm, dry winds which in different districts have been described under the names *foehn* and *chinook* are the inevitable consequence of such conditions, and are, moreover, particularly characteristic of steep mountain slopes more or less covered by glaciers. Such foehn winds have long been recognized as especially characteristic of western Greenland. Dr. Henry Rink, who was a pioneer in the scientific study of Greenland, referring to these winds, wrote in 1877:[17] —

Among the *prevailing winds* in Greenland the *warm land wind* is the most remarkable. Its direction varies according to locality from true E.S.E. to E.N.E. always proceeding though warm from the ice-covered interior, and generally following the direction of

the fjord. It blows as frequently and as violently in the north as in the south, but more especially at the fjord heads, while at the same time in certain localities it is scarcely perceptible. It often turns into a sudden gale; the squalls in some fjords rushing down between the high rocks, in certain spots often sweep the surface of the water with the force of a hurricane, raising columns of fog, while the surrounding surface of the sea remains smooth.

Nansen encountered one of these foehn winds on his descent, and Peary mentions their occurrence in the north. In Scoresby's Land on the east coast, a foehn wind in the winter season has been known in a single hour to change the temperature by 24° C. (or 43° F.), and the maximum change during such a wind is far greater. It is not yet known from observations to what distance above the ice surface the winds of the Greenland system extend, or how the broad cyclonic areas of the atmosphere are modified. The anti-cyclone of the continent is, however, none the less clear and constant and is centred over the high interior. Nansen has remarked the calms over the divide of his section.[18]

There is some evidence that in adopting the important modern laws of adiabatic cooling of the air, we have allowed the pendulum to swing too far, and have given too little weight to the effect of cooling through contact of air with either rock or snow. The latest results of Antarctic expeditions furnish the most striking proof of this, if other than Greenland examples were needed, and the Antarctic studies throw much light upon the conditions of snow distribution which are observed in Greenland.

**Wind Transportation of Snow over the Desert of Inland-ice.** — Whymper and Nordenskjöld each called Greenland a "Northern Sahara." In different ways Nansen and Peary have also instituted comparisons between the wastes of snow in the interior of Greenland and the desert of sand of the

Sahara. The Norwegian explorer has emphasized especially the wide daily ranges of temperature, which because of generally cloudless atmospheres, both deserts have in common. Of the monotonous and elemental simplicity of the snow vistas back from the ice margin in North Greenland, Peary says:[19] —

It is an Arctic Sahara, in comparison with which the African Sahara is insignificant. For on this frozen Sahara of inner Greenland occurs no form of life, animal or vegetable; no fragment of rock, no grain of sand is visible. The traveller across its frozen wastes, travelling as I have week after week, sees outside himself and his own party but three things in all the world, namely, the infinite expanse of the frozen plain, the infinite dome of the cold blue sky, and the cold white sun — nothing but these (see Fig. 86).

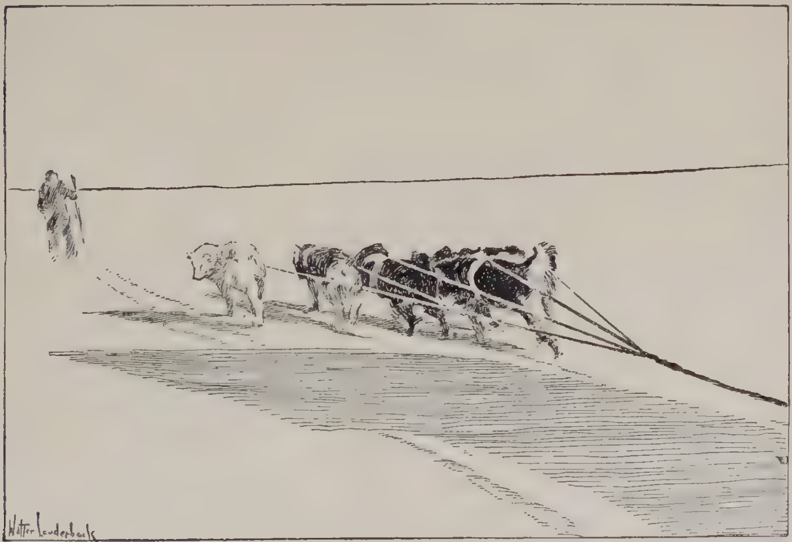

FIG. 86. — On the Sahara of snow (after Peary).

There is, however, yet another marked parallel between the snow waste and the sand desert. It is the importance of wind as a transporting agent. In his shorter acquaintance

with southern Greenland Nansen was less impressed with this, but he has explained the secondary snow ridges upon the marginal terraces of the inland-ice as wind accumulations.[20] These long parallel ranges of snow drift thus correspond to the similar ranges of sand dunes which sometimes throughout a width of many miles hem in the deserts of lower latitudes. In northern Greenland Peary's observations have a special value. He says:[21] —

> There is one thing of especial interest to the glacialist — the transportation of snow on the ice-cap by the wind. . . .
>
> The opinion has been forced upon me that the wind, with its transporting effect upon the loose snow of the ice-cap, must be counted as one of the most potent factors in preventing the increase in height of the ice-cap — a factor equal perhaps to the combined effects of evaporation, littoral and subglacial melting, and glacial discharge. I have walked for days in an incessant sibilant drift of flying snow, rising to the height of the knees, sometimes to the height of the head. If the wind becomes a gale, the air will be thick with the blinding drift to the height of 100 feet or more. I have seen in the autumn storms in this region round an amphitheatre of some 15 miles, snow pouring down in a way that reminds one of Niagara.[22] When it is remembered that this flow of the atmosphere from the cold heights of the interior ice-cap to the lower land of the coast is going on throughout the year with greater or less intensity, and that a fine sheet of snow is being thus carried beyond the ice-cap, to the ice-free land at every foot of the periphery of the ice-cap, it will perhaps be seen that the above assumption is not excessive. I feel confident that an investigation of the actual amount of this transfer of snow by the wind is well worth the attention of all glacialists.

**Fringing Glaciers Formed from Wind Drift.** — In the vicinity of Inglefield Gulf in northwest Greenland, the inland-ice ends in a steep, snowy slope rising to a height of about 100 feet, where is a terminal moraine, above which moraine rises the great dome of the inland-ice. The whiteness and freshness of a portion of the snow of the outer border, when

examined by Chamberlin,[23] showed it to be wind drift of recent accumulation. Locally, however, older and discolored snow appeared beneath the whiter surface snow, and in a few places stratified granular ice with some included rock débris. This snow and ice becomes augmented from year to year and is, in Chamberlin's opinion, a species of *fringing glacier.* Such fringes were from a few rods to a half mile in breadth, and where a favorable depression existed, one was observed extending for a mile or more down the valley. Commander Peary has found this a dominant feature on the north Greenland coast. Fringing glaciers of this type have also been described by Salisbury from the vicinity of Melville Bay. Their movement was clearly evinced by their structure and by the débris which they carried.[24]

**Nature of the Surface Snow of the Inland-ice.** — The surface snow from the marginal zones of the inland-ice has the granular form characteristic of *névés*, as has been shown with exceptional clearness in elaborate studies by von Drygalski.[25] Such grains, grown by accretions from a single crystal nucleus and at the expense of neighboring crystals, must require either fusion from temporary elevation of temperature, or from pressure. The observations of von Drygalski were made on the ice of the marginal tongues and on the blue layers of the inland-ice; but as the samples taken farthest from the margins were found at a height of only 500 meters, the results throw little light upon the conditions of surface snow within the interior, where melting does not take place. In view of Nordenskjöld's observations in Spitzbergen[26] and recent studies in Antarctica it is unlikely that firn or névé snow will be found within the interior except at some depths below the surface.

Nansen has described the fine " frost snow " which falls

almost daily from an air layer near the snow surface, from which its moisture has been derived. Melting does not occur there, as already stated, except, perhaps, for a few days in the height of summer when a thin crust develops upon the surface.[27] Peary has referred to the snow at the highest altitudes which he reached in north Greenland as "unchanging and incoherent." This dry hard snow chased by the wind, has the cutting effect of sand in a blast, and thus is offered still another parallel with deserts and their wind blown sand. Each new storm, we are told by Stein,[28] piles up a snowbank on the lee sides of nunataks, but the next storm, coming from a somewhat different direction and laden with fine hard snow, cuts away the earlier deposit as would a sand blast. Peary discovered one of his earlier snow huts partly cut away by this process.

**Snow Drift Forms of Deposition and Erosion — Sastrugi.** — The minor inequalities of the snow surface as determined by the wind blowing over the inland-ice, have been mentioned more or less persistently by all Arctic travellers, since upon the character of this surface has so largely depended the celerity of movement in sledge journeys. It is unfortunate that no one has discussed the subject from a scientific standpoint, for it has great significance in connection with the study of the strength and direction of the wind over the snow surface. All minor hummocks and ridges of this nature are included under the general term *sastrugi* (see Fig. 87).

The student may learn much concerning their form within the Antarctic regions from examination of the many beautiful photographs recently published by the Royal Society in connection with the British Antarctic Expedition.[29] On plate 92 of this collection, sastrugi are shown which were originally laid down in "elongated domes" and "crescent

hollows," but which on account of change in the wind direction the drifting snow granules have cut away both on the soft surface and in the harder deep layers. As a result of this erosion cross flutings have been superimposed upon the original forms.

Our best study of snow drift forms has been made by Dr.

FIG. 87. — Sastrugi on the inland-ice of North Greenland (after Peary).

Vaughan Cornish, who, after a series of monographs dealing with waves in other materials, has spent a winter in Canada in order to study the phenomena connected with the drifting of snow.[30] It is found that snow which falls at temperatures near 32° F. is wet and sticky, and behaves quite differently from that which falls near or below the zero of the same scale; which, on the contrary, is dry and slippery. Subsequent modifications of either of these forms of snow depend chiefly upon pressure, temperature, radiation, and

wind. It is the cold, dry, and granular snow only which makes so-called *normal* waves, and it must be this form which plays the major rôle in producing the surface irregularities of the inland-ice of Greenland.

Ripples and larger waves alike, when formed from granular snow and when shaped by wind accumulation, *have the steep side always to leeward*, in which respect the snow behaves like drifted sand. In order to produce waves or ripples, the wind must have a velocity sufficient to be thrown into undulations by the irregularities of the surface over which it blows. The most perfectly moulded forms are naturally produced upon a relatively plane surface, such as is realized on the inland-ice of Greenland — the "imperial highway" of Commander Peary.

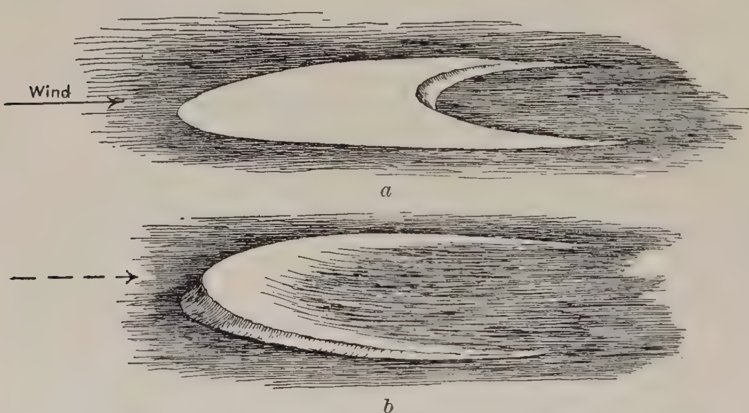


FIG. 88. — Barchans in snow. *a*, of deposition; *b*, of erosion (after Cornish).

Apparently the direction of the greatest extension of the sastrugi will depend upon the strength of the wind and upon the amount of snow which is being transported, much as has been found to be the case with drifted sand.[31] Thus, with small amounts of snow and moderate winds, the characteristic form of sastrugi is a short, scalloped ridge lying across the wind direction and in form not unlike an ox-yoke —

something intermediate between a barchan and a transverse ridge. Barchans of snow almost identical in form with sand barchans, are produced apparently under like conditions, the chief differences being that lighter winds suffice to accomplish the result with the less ponderous snow, and that the resulting forms set quicker in the snow (see Fig. 88 *a*).

Cornish has realized the full importance of snow-blast erosion in modifying the form of snow drifts. His *barchans of erosion,* in plan resemble the barchans of deposition from which they are derived, but unlike the depositional forms their broader surface is concave upward instead of convex, and their steeper face is toward the wind (see Fig. 88 *b*).

Some facts of importance which concern the density of the snow are emphasized by Cornish, and apply with especial force to the surface snow of inland-ice. It was found that crusts upon the surface of snow do not necessarily imply melting, but are produced in temperatures below the fusion point. When the air temperatures at Winnipeg ranged from 25° to − 28° F. the snow surface over the river set so hard that the moccasined heel did not dent it. Pieces of this snow broken off and held up to the sunlight showed a "mosaic of small translucent icy blocks cemented firmly by opaque ice." The effect upon snow density of the radiation from the surface and of pressure from the wind, were strikingly brought out by a number of observations. Newly fallen snow in Canada has a density of about 0.1. Over the level surface about Winnipeg in the month of January and at a temperature of 10° F., the snow was found to have a density within the upper two feet of 0.38; while in the woods at the same time and at the same depth, here without a crust, its density was 0.19. Thus it is seen that the snow in the woods is about twice as heavy as newly fallen snow, but only about half as heavy as that which has been chased about by the wind. At Glacier House in the Selkirks, where

the snow is shielded from the wind within a narrow valley, experiments showed a density of 0.106 at the surface, whereas at a depth of one foot below the surface the density was 0.195, and at a depth of four feet, 1.354. The middle value being that of the snow in the woods at Winnipeg, it is seen that the weight of an additional three feet of snow is necessary in order to pack snow as tightly as is done by the wind blowing over the prairie. After a time, as a result of this treatment by the wind, an eight-inch snowfall dwindles by packing in the woods to four inches, and over the open plain to a two-inch layer. According to Gourdon, a cubic metre of Antarctic snow may exceed 700 kilogrammes in weight.[32]

In eroding a drift, the wind first attacks the softer surface layer. This removed, the snow of the blast adheres less to the surface of the drift, and in consequence abrades it more vigorously. Thus, notches in the ridges, instead of being mended by the detritus, are increased by it, and transverse ridges are presently cut through, and we pass by stages from an arrangement of ridges transverse to the wind to that of longitudinal structures having the greatest extension parallel to the wind.[33] These longitudinal sastrugi appear to be the dominant ones, and from them the direction of prevailing winds may be determined as has been already proven in the Antarctic. On the Siberian tundras the sastrugi are often the only guides of direction which the natives have.[34]

**Source of the Snow in Cirrus Clouds.** — What has been learned of the circulation of air above the continental ice of Greenland, makes it extremely unlikely that any such excessive alimentation upon the eastern margin through ordinary snow fall, as has been advocated by von Drygalski, can occur.[35] Such moisture-laden air as can, under normal conditions, reach the interior plateau must descend from higher levels in the anti-cyclone above the central boss, and be

distributed by the outward flowing surface currents. From such altitudes the moisture would probably be congealed in the form of fine ice needles, such as are believed to exist in cirrus clouds. This ice, in descending to the plateau, would be adiabatically heated with, as a consequence, the melting and vaporization of the ice crystals, which on reaching the cold air layer directly enveloping the ice surface would be congealed without passing through the cloud stage, thus yielding the characteristic frost snow. This process will be more fully treated in part III, after Antarctic ice masses have been considered. Of greatest interest in this connection, is the observation of Nansen that while the sky was, during the time of his crossing, in the main clear, those clouds which were present were generally either cirrus clouds or some combination of cirrus with cumulus and stratus clouds. No cumulus clouds whatever were observed. In tabular form his results are as follows:

| Form of Clouds | No. of Days | | Per Cent. |
|---|---|---|---|
| Cirrus . . . . . . . . . . . | 23 | 51 | 44 |
| Cirro-stratus . . . . . . . . . | 17 | | 33 |
| Cirro-cumulus . . . . . . . . . | 11 | | 21 |
| Cumulo-stratus . . . . . . . | 22 | | 42 |
| Stratus . . . . . . . . . . . | 10 | | 19 |

As already stated, such snow as reaches the central area must, it would seem, be derived from the cirrus clouds which at higher levels move in toward the anti-cyclone and descend in its center to become outward flowing surface currents over the "Great Ice." This subject will be more fully developed in connection with the Antarctic continental glacier (Chapter XVI).

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[1] Robert Stein, "Suggestion of a Scientific Expedition to the center of Greenland," Congrés Intern. pour l'Étude des Regions Polaires, Brussels, 1906, pp. 1–4 (separate).

[2] In the light of later studies this may as satisfactorily be explained through hardening by the wind.

[3] Mohn u. Nansen, *l. c.*, p. 86.

[4] Nansen, *l. c.*, vol. **1**, p. 495.

[5] Nansen, *l. c.*, vol. **2**, p. 56.

[6] *Geogr. Jour.*, vol. **11**, 1898, p. 228.

[7] Mohn u. Nansen, *l. c.*, pp. 109–111.

[8] Nansen, *l. c.*, vol. **2**, p. 491. See also Peary, *Geogr. Journ.*, *l. c.*, p. 214.

[9] Mohn u. Nansen, *l. c.*, pp. 44–45.

[10] E. v. Drygalski, "Die Eisbewegung, ihre physikalischen Ursachen und ihre geographischen Wirkungen," *Pet. Mitt.*, vol. **44**, 1898, pp. 55–64. See also by the same author, "Grönland-Expedition," etc., pp. 533–539.

[11] Nansen, *l. c.*, vol. **2**, p. 496. Also Mohn and Nansen, *l. c.*, pp. 44–47.

[12] "Journeys in North Greenland," *Geogr. Jour.*, vol. **11**, 1898, pp. 233–234. See also "Northward over the 'Great Ice,'" vol. **1**, pp. lxix–lxx.

[13] Lieut. A. Trolle, R. D. N., "The Danish Northeast Greenland Expedition," *Scot. Geogr. Mag.*, vol. **25**, 1909, pp. 57–70 (map and illustrations).

[14] Nansen, *l. c.*, vol. **2**, p. 496.

[15] *Jour. Geol.*, vol. **3**, 1895, pp. 578–579.

[16] Professor v. Drygalski has shown that on the Great Karajak glacier near the coast in central western Greenland, the temperature of the snow and ice down to a depth of 60 feet or more undergoes a fall of temperature in response to the severity of the winter's cold, but in time this fall in temperature lags behind the period of maximum cold. Below that depth, however, it approximates in temperature to the zero of the centigrade scale. Temperatures of the snow measured just below the surface, varied from $-11°$ to $-26°$ C. (E. von Drygalski, "Grönland-Expedition der Gesellschaft für Erdkunde zu Berlin," 1891–1893, vol. **1**, 1897, pp. 470–472.)

[17] Henry Rink, "Danish Greenland, Its People and Its Products," London, 1877, p. 468.

[18] Nansen, *l. c.*, vol. **2**, pp. 487–488, 496.

[19] *Geogr. Journ.*, *l. c.*, pp. 214, 215.

[20] Mohn u. Nansen, *l. c.*, p. 78.

[21] *Geogr. Jour.*, *l. c.*, pp. 233–234.

[22] See Nordenskjöld *ante*, p. 114.

[23] T. C. Chamberlin, "Glacial Studies in Greenland, VI.," *Jour. Geol.*, vol. **3**, 1895, pp. 580–581.

[24] Salisbury, *Jour. Geol.*, vol. **3**, p. 886.

[25] "Grönland-Expedition," etc., vol. **1**, 1897. See also C. H. Ryder,

Undersogelse af Grönlands vestkyst fra 72° till 74° 35′, 1886–1887, *Meddelelser om Grönland*, heft 8, pl. xvii.

[26] A. E. Nordenskjöld, "Die Schlittenfahrt der Schwedischen Expedition im nordöstlichen Theile von Spitzbergen," 24 April–15 Juni, *Pet. Mitt.*, vol. **19**, 1873, pp. 450–453.

[27] "Thus it will be seen that at no great distance from the east coast the surface of dry snow begins, on which the sun has no other effect than to form a thin crust of ice. The whole of the surface of the interior is entirely the same." (Nansen, *l. c.*, vol. **2**, p. 478.)

[28] Robt. Stein, Congrés international pour l'étude des regions polaires, Brussels, 1906, pp. 1–4 (separate).

[29] National Antarctic Expedition, 1901–4. Album of photographs and sketches (with brief descriptions, Ed.), London, 1908.

[30] Vaughan Cornish, "On Snow-waves and Snow-drifts in Canada," *Geogr. Jour.*, vol. **20**, 1902, pp. 137–175.

[31] P. N. Tschirwinsky, "Schneedunen und Schneebarchane in ihrer Beziehungen zu äolischen Schneeablagerungen im Allgemeinen," *Zeitsch. f. Gletscherk.*, vol. **2**, 1907, pp. 103–112.

[32] E. Gourdon, Expédition Antarctique Française, 1903–1905, Glaciologie, Paris, 1908, p. 75.

[33] Cornish, *l. c.*, pp. 159–160.

[34] Tschirwinsky, *l. c.*, p. 107.

[35] "The east is to be regarded as the region of origin of snow, the west as the terminal region of the Greenlandic glaciation." (E. von Drygalski, "Die Eisbewegung, ihre physikalischen Ursachen und ihre geographischen Wirkungen," *Pet. Mitt.*, vol. **44**, 1898, pp. 55–64.)

# CHAPTER X

## DEPLETION OF THE GREENLAND ICE FROM SURFACE MELTING

**Eastern and Western Slopes Compared.** — Though it is probably not true, as has been claimed by von Drygalski, that the eastern border of the continent is the locus of nourishment for the ice, it is almost certain that the losses are much greater along the western margins. For this there are several reasons. In the first place, the eastern base is apparently characterized by lower temperatures. The cold ocean current, which carries ice bergs and floes from the Arctic Ocean southward in Baffin's Bay, follows the western shore, while a warmer counter current flows northward along the eastern or Greenland coast at least in its southern stretches. Tarr thinks this current may reach as far as Melville Bay.[1]

Again, ablation or surface melting is to a large extent dependent upon the quantity of rock débris which is blown onto the ice surface from its margins.[2] In southern Greenland, at least, the wider ribbon of exposed shore land upon the western coast conspires with the prevailing westerly winds to make a more effective marginal attack upon the anti-cyclone of the continent. Nansen reports that he found on the east coast none of the rock dust first described by Nordenskjöld as "cryoconite," though it extended inward from the western coast as much as 30 kilometres.[3]

Still further it is to be remembered that the ice of the west margin is intersected by many deep fjords, which communicating with the open sea, remove an enormous quantity of ice in the form of bergs. Upon the eastern coast, the pack-ice prevents the removal of bergs except from the southern latitudes.

**Effect of the Warm Season Within the Marginal Zones of the Inland-ice.** — In winter the entire surface of the ice, and the border of the land as well, are covered with an unbroken layer of fine, dry snow. The suddenness of the change to summer within the land zone outside the ice front has been emphasized by Trolle. The temperature of the snow upon the land in northeast Greenland rose gradually with the arrival of summer until the melting-point was reached, and then in one day all the snow melted. "The rivers were rushing along, flowers were budding forth, and in the air the butterflies were fluttering." [4]

The snow upon the surface of the inland-ice, where studied by von Drygalski within the western marginal zone, was found to have temperatures which in the winter season were normally lowest just below the surface, and which approximated to the zero of the centigrade scale at depths of generally a few metres only. In October with a sub-surface temperature of $-11°$ C. the zone of zero temperature was reached at a depth of a little more than 2 metres. The sub-surface temperature steadily lowered from this time as the colder months came on, and the depth of zero temperature descended to below the limit of the experiments, which was only a little more than 2 meters. The form of the temperature curves in dependence upon depth showed clearly, however, that at very moderate depths equalization occurred. Late in March the lowest temperatures were reached with $-26.3°$ C. for the immediate sub-surface temperature, and $-9°$ C. for the temperature at depth of

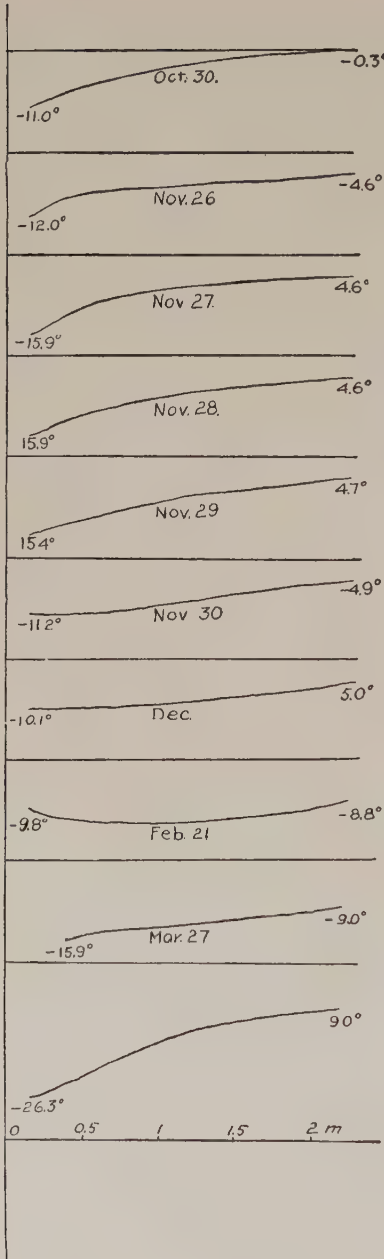



Fig. 89. — Diagrams showing the distribution of temperatures within the surface zones of the inland-ice (after Von Drygalski).

2 metres. Warm weather at the surface resulted in a warm wave which descended through the snow, following the colder one, and so resulted in a maximum temperature not immediately below the surface, but at increasing distances from it depending upon the duration of the warmer air temperatures at the surface. Thus, a ten day foehn in January raised the temperature at a depth of 2.2 metres, by half a degree. It required over two days for this rise in temperature to proceed to a depth of 1 meter, and ten days for it to reach the depth of 2 meters. Similar effects are produced with the coming of the more prolonged warm weather of the summer season (see Fig. 89).[5]

When the surface zone of the snow has reached the fusing-point of snow, melting begins rapidly. Peary has drawn a graphic picture of the effect of the

warm season upon the margins of the Greenland ice. Late in the spring the warmth of the sun at midday softens the surface first along the outermost borders of the ice, and this, freezing at night, forms a light crust. Gradually this crust extends up in the direction of the interior, and as the season advances the surface of the marginal rim becomes saturated with water. This zone of slush follows behind the crust towards the interior in a continually widening zone as the summer advances. Within the outermost zone


Fig. 90. — Map showing the superglacial streams within the marginal zone of the inland-ice of Greenland (after Nordenskjöld).

the ice is so decomposed that pools come to occupy depressions upon the surface, and streams cut deep gullies into the ice. At the same time, the ice shows a more dirty appearance through the concentration of the rock débris due to the melting of surface layers of ice. By the end of the season, pebbles, boulders, and moraines have in places made their appearance on the surface, and the streams have left a surface of almost impassable roughness.[6]

**Differential Surface Melting of the Ice.** — In his ascent of the western margin of the ice near the latitude of Disco Bay,

Peary encountered lakes surrounded by morasses of water saturated with snow. The ice within this zone is crevassed, and down the fissures some of the surface streams disappear, at times in a large water-fall, and again in a "mill" of its own shaping. Baron Nordenskjöld earlier observed almost identically the same phenomena along the line of his route. The intricate ramifications of the superglacial rivers and the occupation of almost the entire remaining surface of the ice by shallow ice wells and basins along his route are shown in

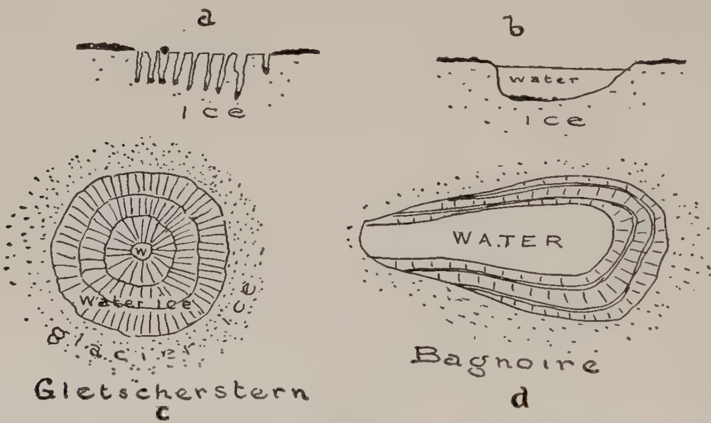



FIG. 91. — Diagrams to show the effects on differential melting on the ice surface: *a*, dust wells; *b*, basins; *c*, glacier stars; *d*, bagnoires.

Figs. 90 and 93.[7] These ice wells are in no wise restricted to inland-ice, but are found on mountain glaciers as well, and represent but one of a series of allied phenomena dependent upon differential melting due to the presence of rock fragments upon the ice.

The influence of heat radiated from rock particles which lie upon the surface of snow or ice, has never been properly recognized. During the construction of the Bergen Railway, which was completed across Norway in December, 1909, it was necessary each summer to clear away great banks of snow lying upon the right of way, before the work of the sea-

son could be said to be begun. The labors of an army of shovellers which had at first made somewhat ineffectual attacks upon the drifts, were later replaced by the sun, a layer of earth or sand having been spread over the snow surface. In this way it was learned that drifts which would otherwise have been but little diminished in size sank as much as six feet in the course of a month.

Ice wells and allied phenomena due to differential melting about rock particles on the ice surface were described by

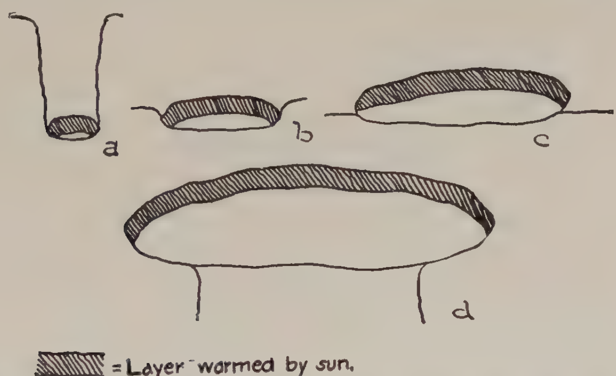



FIG. 92. — Fragments of rock of different sizes to show their effect upon melting on the ice surface.

Agassiz in his "System Glaciare." The particles of rock if not contiguous upon the ice surface absorb the sun's rays and cause excessive melting of the ice about and beneath them. They thus sink down into the ice and form dust wells (Fig. 91, *a*). The thin walls which separate those wells which are close together, being now attacked by the warm air on their sides instead of on the top only, they in their turn melt away to form a small basin, which soon either wholly or in part fills with water (Fig. 91, *b*). Where in contact with their neighbors and where of such thickness of accumulation as not to be heated through by the sun's rays, these rock particles behave in quite a different manner and protect the ice

beneath them from the sun (note margins of wells and basins in Fig. 91, *a* and *b*). The same effect is brought about if the fragments are too large, for the thickness of surface layer of rock which can be sensibly warmed by the sun's rays is quite independent of the size of the fragment. Thus the familiar ice tables developed especially upon mountain glaciers are formed. Fig. 92 brings this out by showing the relation of the warmed surface layer to the whole fragment — (*a*) in a dust well, (*b*) in a pebble that sinks slightly into the ice until it reaches equilibrium, (*c*) in a slab of such size as to neither facilitate nor retard surface melting, and (*d*) in a large protective slab of rock.

The basins which result from the dust wells induce still other interesting structures. At night the water within these

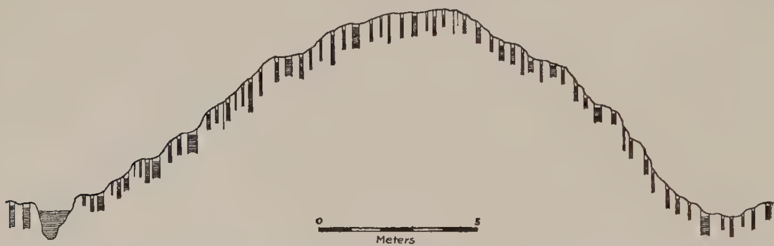



Fig. 93. — Section of the so-called "cryoconite holes" upon the surface of an ice hummock (after Nordenskjöld).

basins freezes in the form of needles which everywhere project inward from the steep walls of the basin. After repeated freezings the basins are often entirely closed by these needles and thus form "glacier stars" (see Fig. 91, *c*). Elongated basins have been given the name bagnoires (see Fig. 91, *d*).

From studies of such phenomena resulting from differential melting as developed upon the Great Aletsch Glacier, we have found that the segregation of the rock débris upon the bottom of the basins later protects those areas after melting of the general surface has drained them of their water. Thus

the familiar débris-covered ice cones come into existence and further increase the irregularities of the ice surface. The dust wells and basins which were described by Nordenskjöld over large areas covered the sides of steep hummocks in the ice as well as its more level surfaces (see Fig. 93).

On his return from his attack upon the inland-ice near Disco Bay, Peary travelled for seven hours through half-frozen morasses alternating with hard blue ice honeycombed with water cavities. Then the character of the ice completely changed, the slush and the water cavities disappeared, and the entire surface was granular snow-ice, scored in every direction with furrows, one to four feet deep, and two to ten feet in width, with a little stream at the bottom of each.[8]

**Moats Between Rock and Ice Masses.** — Wherever the ice sends an outlet down a valley, the edges of this ice shrink away from the warmer rocks on either side, thus leaving lateral canyons walled with ice on the one hand and with rock upon the other. Down these canyons are the courses of glacial streams.[9] An excellent example of such a lateral stream is furnished by the Benedict glacier (Plate 25, A).[10]

In most cases where nunataks project through the ice surface, the absorption of the sun's rays by the rock melts back the ice so as to leave a deep trench surrounding the island and much resembling the moat about an ancient castle. Snow drifted by the wind often bridges or partially fills the moat. Upon nunataks forty miles within the border of the ice in northeast Greenland the Danes found water running in the ravines and disappearing under the ice at the margin of the nunatak where it "formed the most fantastic ice-grottoes, where the light was broken into all colors through the crystal icicles."[11]

Such moats have been mentioned by nearly all explorers upon the ice. It has been claimed by von Drygalski that this phenomenon is characteristic of the west coast margin

only, more ample nourishment upon the eastern coast making the snow rise about the rock like a water meniscus. Ryder [12] and Jensen [13] have each figured such moats from the extreme south of Greenland. By Jensen's party these moats were made use of for camping-places. Peary, however, has shown that the moats upon the west coast are often largely filled with snow.[14] Stein mentions this as a common feature after snow storms,[15] and Chamberlin [16] asserts that wherever the motion of the ice is considerable the trench does not appear, but the ice impinges forcibly upon the base of the nunatak.

**Englacial and Subglacial Drainage of the Inland-ice.** — In addition to the superglacial streams which are so much in evidence, others which are englacial run beneath the surface of the ice, as has often been discerned by putting the ear close to the ice surface. Nordenskjöld reports one instance where water spouted up from the surface mixed with a good deal of air and spray.[17] Salisbury also has mentioned a huge spring upon the surface of the ice in north Greenland that shot up to a distance of not less than ten feet above the bottom of the basin from which it issued. Owing to the fact that near the margin of the ice its surface is much crevassed, comparatively little water can continue to the border in surface streams. Salisbury mentions an instance where an englacial stream with a diameter of about five feet issued from the vertical face which formed the ice front. Most of the water flowing upon the surface descended, however, to the bottom, and issued largely below the surface of the fluvio-glacial materials. It is, he says, a rare exception to find a visible stream issuing from beneath the ice at its margin. In most cases, the water undoubtedly comes out in quantities, though beneath the surface of the outwash apron, as could be detected by the ear.[18] Peary has observed that a greater abundance of water issues from beneath the ice-cap in extreme northeastern than in northwestern Greenland.[19]

*A*. Lateral glacial stream flowing between ice and rock, Benedict glacier tongue (after Peary).

*B* The ice-dammed lake Argentino in Patagonia (after Sir Martin Conway).

**The Marginal Lakes.** — Wherever the ice has withdrawn from the rock surface, and where ice drainage permits of it, small lakes marginal to the inland-ice have come into existence. Special interest attaches, however, to those bodies of water which are impounded by the ice itself along its margin, because of the light which is thrown upon the origin of somewhat similar bodies of water about the great continental glaciers of Europe and North America during late Pleistocene times. Attention was called to such ice-

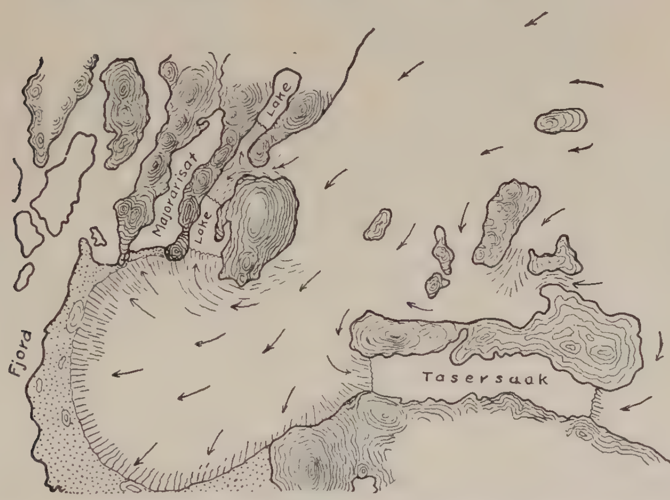



FIG. 94. — Map showing the margin of the Frederikshaab ice apron extending from the inland-ice of Greenland and showing the position of ice-dammed marginal lakes (after Jensen).

dammed lakes situated upon the margin of the Frederikshaab tongue of the inland-ice by the Jensen, Kornerup, and Groth expedition of 1878. A map of this region was published by Jensen (see Fig. 94).[20] Here the lakes filled with water from the melting of the glacier by which their outlets are blocked, stand at different levels. The Tasersuak on the south, standing at a level of 940 feet above the sea, is blocked by ice at both ends and is covered by bergs which are calved

from the ice cliffs. This lake drains through a canal upon the ice to a much smaller lake standing at a level of 640 feet, and thence through a small river to the head of the Tiningerfjord. To the northward of the apron of ice another long fjord is blocked by a T-shaped extension of ice into its central portion. Thus there result two fresh water lakes standing at different levels, the lower one, like the Tasersuak, with ice cliffs at both ends, and the other blocked at one end only by the ice. A slight retreat of the inland-ice of this district would retire the T-shaped extension of the glacier, and the two smaller lakes would thus become united into one at the level of the lower. A still further withdrawal of the Frederikshaab glacier tongue would open an outlet for this lake to the

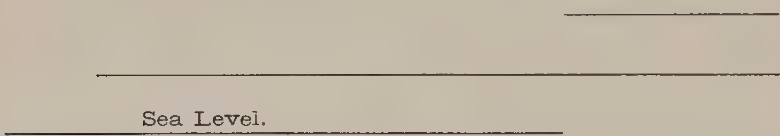



Fig. 95. — Diagram showing arrangement of shore lines from marginal lakes to the northward of the Frederikshaab ice tongue, if its front should retire past the outlet of the lower lake.

sea at a still lower level. Souvenirs of these events would be left in a series of parallel shore lines ascending in step-like succession to the head of the fjord (see Fig. 95). Suess has used this illustration to explain the vexed problem of the *seter*, the abandoned shore lines of Norway, which he claims have this peculiarity of arrangement.[21]

The famous "parallel roads" of glens Roy, Glaster, and Spean in the Scottish highlands, which have in similar manner vexed geologists, but which were finally given a satisfactory explanation by Jamieson,[22] find here a living model. Still later a nearly identical example from Pleistocene times has been supplied from the Green Mountains to the eastward of Lake Champlain.[23]

About the Cornell tongue of the inland-ice of Greenland

are many marginal lakes situated where the border drainage has been blocked by the glacier itself. These lakes have been described by Tarr, who says: [24] —

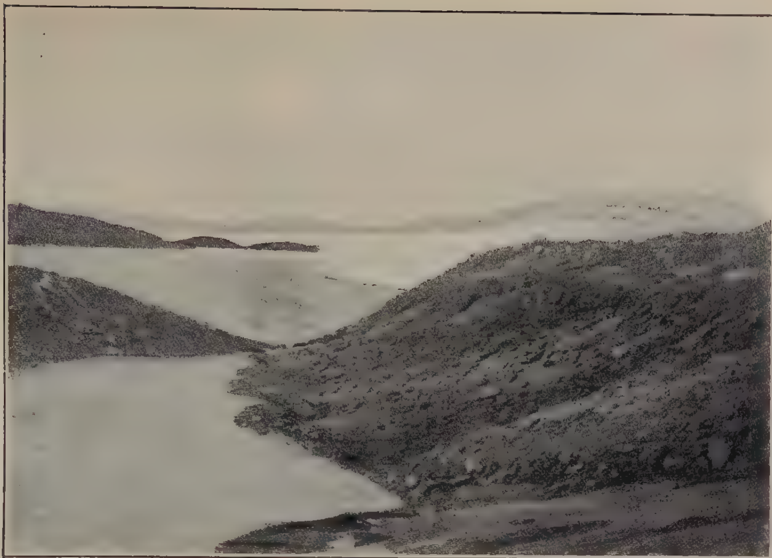
> In its passage down the valley, between the ice and the land, the marginal stream finally enters the sea. During its passage it now and then encounters tongues of ice, and for a distance flows along them, and finally beneath them, where the glacier edge rests against a moraine, or the rock of the land. Again it falls over a rock ledge as a cascade, or even a grand waterfall; and every here and there it is dammed to form a marginal lake. Dozens of these, great and small, were seen along the margin; and they varied in size from tiny pools to ponds half a mile in length, and 200 to 300 yards in width.
>
> Since the water of the marginal streams is everywhere milky with sediment, these lakes are receiving quantities of muddy deposits, and in them tiny deltas are being built. Where the lake waters bathed the ice front little icebergs are coming off, in exactly the same way as in the fjord at the glacier front, and these are bearing out into the lake large rock fragments which are being strewn over the bottom or on the shores. Also at the base of the cliffs, as well as on some of the deltas formed by rapidly flowing streams, pebbles and boulders are being mixed with the clay.
>
> Nearly every lake shows signs of alteration in level resulting from the change in outflow either to some point beneath the ice, when the lake may be entirely drained, or to some lower outlet for the lake opened by a change in the ice front, or by the down cutting of the stream bed where it is eating its way through a morainic dam. The different elevations are plainly evident from the absence of lichens on the rocks, the clay clinging to the rocky shores, and the beach terraces along the old shore lines. In one case, at the western end of Mount Schurman, a lake of this type, with a depth of at least 100 feet has recently been drained. Where these extinct lake beds exist one sees revealed an expanse of muddy bottom with scattered blocks of rock.

In plate 26, *A* and *B* are represented after Tarr, in the one case, one of the marginal lakes, and in the other, the formation of a delta under the conditions described. From the

Karajak district on the northern side of the Upper Nugsuak Peninsula,[25] von Drygalski has described in addition to the usual rock basin lakes left by the withdrawal of the ice front, a true ice-dammed lake which appears upon his map as the *Randsee.*[26]

No one of the marginal lakes thus far described furnishes a parallel to the interesting Pleistocene glacial lakes of the Laurentian basin of North America, since these developed for the most part upon a surface of relatively mild relief, and the shores not formed by the glacier itself were generally moraines registering an earlier position during the retirement of the ice front. Perhaps an existing example comes nearest to being realized in connection with those glaciers which descend the eastern slopes of the Andes and enter the great lakes impounded behind moraines of an earlier extension of the same ice tongues.[27] In these cases the ice fronts of the glaciers are cut back into cliffs from which are derived the bergs that float upon the surface. The ice cliff and some of the bergs of Lake Argentino are shown in plate 25, *B*. According to Moreno, Lake Tyndall is bounded on the west by true inland-ice,[28] the remnant of the larger sheet of Pleistocene times.

**Ice Dams in Extraglacial Drainage.**—In north Greenland outside the ice front, the brooks sometimes offer a striking example of ice obstructions forming by irrigation. This is often the case where their beds are wide and are covered with boulders. The water generally continues to run beneath the stones for a great part of the winter. Later, however, its outlets may freeze up, whereupon the water rises, inundating the stones and covering them with an ice crust. Through successive obstruction, overflowing, and freezing of these streams, the ice dam which results may attain to such a thickness that it is still to be found at these places late in the summer when the ice and snow have elsewhere disappeared from the low land.[29] The significance of such dams as



*A.* Ice-dammed lakes on the margin of the Cornell tongue of the inland-ice (after Tarr).

*B.* Delta in one of the marginal lakes to the Cornell glacier tongue (after Tarr).

obstructions during a readvance of the ice front may well be considerable.

**Submarine Wells in Fjord Heads.** — Rink states that the sea flowing into the fjord in front of the glacier outlet which ends below the water level, is kept in almost continual motion by eddies not unlike those which are seen where springs issue from the bottom of a shallow lake. Such areas upon the surface of the fjord may generally be recognized by the flocks of sea birds which circle above them and now and then dive for food.[30] The existence of such fresh water streams as this implies may also be inferred from the strong seaward current that prevails in the fjords and which is so effective in clearing them of bergs. Such a whirlpool of fresh water or "submarine well" was observed by Rink in the Kvanersokfjord (lat. 62° N.) which was over 100 yards in diameter. The kittiwakes flocked over the spot, and the water was muddy, although no brooks were observed along neighboring shores. This well Rink believed, from reports furnished by the natives, to be much smaller than the similar ones in some other fjords.

According to Rink [31] the lateral lake which borders the inland-ice of Greenland in one of the branches of the Godthaabfjord-Kangersunek suffered changes of level just when the submarine wells before the ice cliff in the fjord showed marked changes in volume. Thus, whenever the water of the lake suddenly subsides, the submarine wells from the bottom of the fjord burst out with violence. On the other hand, when the water in the lake is rising, the wells are relatively quiet. These sudden discharges of the water from lateral lakes, save only that their outlet is submarine, seem thus to be in every way analogous to the spasmodic discharges of the famous Märjelensee upon the margin of the Great Aletsch Glacier in Switzerland. When, as occasionally happens, this lake empties through the opening of a passage beneath

the glacier, the villages which are situated miles below in the valley are suddenly inundated with water.

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[1] R. S. Tarr, "Difference in the Climate of the Greenland and American Sides of Davis' and Baffin's Bay," *Am. Jour. Sci.*, vol. **3**, 1897, pp. 315–320.

[2] An interesting practical illustration of the effectiveness of such débris as a melting agent has been furnished during the construction of the Bergen Railway in Norway, which was completed in December, 1909. A prime factor in the work was a means of clearing the snow so as to prolong the summer season. For this purpose covering the snow surface with fine dirt proved more effective than a corps of shovellers, the sun in this case performing the work.

[3] Mohn und Nansen, *l. c.*, p. 90.

[4] Trolle, *l. c.*, p. 66.

[5] E. von Drygalski, "Grönland-Expedition," *l. c.*, pp. 460–466.

[6] Peary, *Geogr. Jour.*, *l. c.*, p. 218. See also Nordenskjöld, "Grönland" (German ed.), pp. 125–138.

[7] A. E. Nordenskjöld, "Grönland," pp. 197–204, map 3.

[8] *Jour. Am. Geogr. Soc.*, *l. c.*, p. 282.

[9] Peary, *Jour. Am. Geogr. Soc.*, *l. c.*, p. 286.

[10] R. E. Peary, "North Polar Exploration, Field Work of the Peary Arctic Club," 1898–02, Ann. Rept. Board of Regents Smith. Inst. for 1903, 1904, p. 517. Cf. also the almost identical (if smaller scale) effects for Icelandic and Norwegian ice-caps. This volume, ante, p. 101.

[11] Trolle, *Scot. Geogr. Mag.*, vol. **25**, 1909, pp. 65–66.

[12] C. H. Ryder, "Undersogelse af Grönlands Vestkyst fra 72° till 74° 35′, 1886–1887," *Med. om Grönland*, Heft 8, pl. xiii.

[13] J. A. D. Jensen, "Expeditionen till Syd. Grönland," 1878, *ibid.*, Heft 1, pl. iv.

[14] Peary, *Geogr. Jour.*, *l.c.*, p. 217.

[15] Stein, *l. c.*

[16] Chamberlin, *Jour. Geol.*, vol. **3**, 1895, pp. 567–568.

[17] A. E. Nordenskjöld, "Grönland," p. 137.

[18] Salisbury, *l. c.*, pp. 806–7.

[19] Peary, *Geogr. Jour.*, *l. c.*, p. 224.

[20] *Meddelelser om Grönland*, Heft 1. This map has been many times copied, best by Nordenskjöld in his "Grönland" on p. 161.

[21] Beside the Jakobshavn ice tongue, there is another lake confined in like manner to the Tasersuak. (Ed. Suess, "The Face of the Earth," vol. **2**, pp. 346–363.)

[22] Thomas T. Jamieson, On the parallel roads of Glen Roy and their place in the history of the glacial period. *Quart. Jour. Geol. Soc.*, vol. **19**, 1863, pp. 235–259.

[23] H. E. Merwin, "Some late Wisconsin and Post-Wisconsin Shore-lines

of Northwestern Vermont," *Rept. Vermont State Geologist*, 1907–08, pp. 113–137, pl. 21.

[24] R. S. Tarr, "The Margin of the Cornell Glacier," *Am. Geol.*, vol. **20**, 1897, pp. 150–151.

[25] " The Cornell tongue is situated upon the southern side of the same Peninsula."

[26] E. von Drygalski, "Grönland-Expedition," vol. **1**, pp. 61–63, map 2.

[27] Francisco P. Moreno, "Explorations in Patagonia," *Geogr. Jour.*, vol. **14**, 1899, pp. 253–256. Also Hans Steffen, "The Patagonian Cordillera and its Main Rivers between 41° and 48° South latitude," *ibid.*, vol. **16**, 1900, pp. 203–206. Also Sir Martin Conway, "Aconcagua and Tierra del Fuego," London, 1902, pp. 134–135.

[28] See also P. D. Quensel, "On the Influence of the Ice Age on the Continental watershed of Patagonia," *Bull. Geol. Inst. Upsala*, vol. **9**, 1910, pp. 60–92, 2 maps. See also, R. Hauthal, " Der Bismarck-Gletscher, ein vorrückender Gletscher in der patagonischen Cordillere," *Zeit. f. Gletscherk.*, vol. **5**, 1910, pp. 133–143, figs. 1–7.

[29] Henry Rink, "Danish Greenland, Its People and its Products," London, 1877, p. 366.

[30] Rink, *l. c.*, pp. 50, 360–363.

[31] Rink, *l. c.*

# CHAPTER XI

## DISCHARGE OF BERGS FROM THE ICE FRONT

**The Ice Cliff at Fjord Heads.** — Wherever the inland-ice reaches the sea in the fjord heads, and where it comes directly to the sea in broad fronts, as it does near Melville Bay, at Jökull Bay, and on the north side of Northeast Foreland, it is here attacked directly by the waves and is further undermined through melting in the water. The crevassing of its surface over the generally steep descents to the fjords, in a large measure facilitates the attack of the water upon the ice by offering planes of weakness similar to the joint planes in rock cliffs attacked by the sea on headlands. The fjords, though often quite narrow, are generally of great depth, so that, although the ice cliff often rises to a height of several hundred feet, its base probably rests upon the bottom of the fjord. To this a possible exception has been noted for the great Karajak glacier, of which a relatively flat front section may be assumed to be the surface of a floating portion (see Fig. 96).[1] To this interesting example of a floating glacier outlet in connection with the inland-ice of the northern hemisphere, we may recall the probably floating front of the Turner glacier, a dendritic glacier of the tide-water type in Alaska. For its type this example is apparently unique.[2]

**Manner of Birth of Bergs from Studies in Alaska.** — The birth of bergs from the parent glacier has been often described

by travellers, and the superlatives of the language have been drawn upon to express the grandeur and beauty of the observed phenomena. Simple as the process may appear to the casual tourist who makes the usual summer excursion to Alaska, it is not free from serious difficulties, and has given

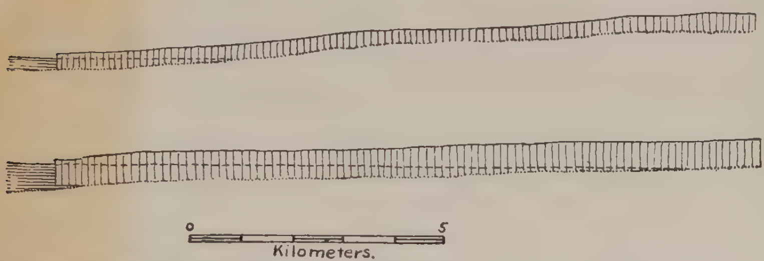


FIG. 96. — Sections from the inland-ice through the Great and Little Karajak outlets to the Karajak fjord (after Von Drygalski).

rise to conflicting views among specialists. The water in front of the ice cliff is generally so muddy, and the danger of approaching the ice front so great, that exact data are necessarily difficult to obtain. The smaller bergs composed of white ice, which are seen to fall into the water from the cliffs at almost all hours, offer no difficulties of explanation, but they are likewise without great significance as concerns the manner of formation of those great floating masses of ice which are carried far to sea and scattered over wide areas of the ocean before their final dissolution in the warmer southern waters. It is, however, interesting to find that the overriding of the lower layers of the ice by the upper greatly facilitates the separation of this type of small iceberg. Engell, who has studied the Greenland icebergs, shows that while this is true of icebergs formed in fjord heads, it plays no part with those calved from the sides of glacier outlets where ice dammed lakes (see below) make iceberg formation possible.[3]

The larger bergs, instead of falling from the cliffs, suddenly

rise out of the water as ice-islands, often several hundred feet in front of the ice cliff. A wholly satisfactory solution of the problem of their birth involves a nice quantitative adjustment of several factors, all of which are undoubtedly more or less concerned. On the one hand, there is wave action which is effective especially near the water level and has a direct range of action extending from a distance below the surface equal to the length of a storm wave in the fjord, and to a height above the quiet level equal to the height of the wave's dash. If there were no melting in the water, and if the lower layers of the glacier moved forward as rapidly as the upper, the tendency would undoubtedly be to develop an erosion profile in every way like that of a rock-cut terrace upon the sea shore. With emphasis upon this element in the problem Russell has assumed that the ice cliff in the fjord is prolonged outward beneath the water as an ice foot which thins gradually toward the toe. Upon this hypothesis the bergs which rise from the water are born from the foot where the increasing buoyancy of the outer portion overcomes the cohesive strength of the material at the surface where rupture occurs. This view accounts particularly well for those bergs which rise from the water far in advance of the cliff (see Fig. 97).[4]

Fig. 97. — Origin of bergs as a result especially of wave erosion (after Russell).

Laying stress rather upon melting in the water and upon the rapid forward movement of the upper layers of ice near the glacier margin, Reid has arrived at a wholly different conclusion concerning the origin of larger bergs:[5] —

The more rapid motion of the upper part would result in its projection beyond the lower part, and this would become greater and greater until its weight was sufficient in itself to break it off. The extent of the projection before a break would occur, depends evidently upon the strength of the ice. . . . That the ice for several hundred feet below the surface does not in general project farther than that above is evident from the fact that I have frequently seen large masses, extending to the very top of the ice front, shear off and sink vertically into the water, disappear for some seconds, and then rise again almost to their original height *before* turning over. If there were any projection within 300 feet of the surface, this mass would have struck it and been overturned so that it could not have arisen vertically out of the water.

Reid thinks there are three ways in which bergs come into existence at the end of a glacier: —

(*a*) A piece may break off and fall over — this is the usual way with small pinnacles; (*b*) a piece may shear off and sink into the water — this is the usual way with the larger masses; or, again, (*c*) ice may become detached under water and rise to the surface.

The supposed successive forms of the ice front, according to Reid, are shown in Fig. 98.

It is easy to see that Russell's and Reid's views might each apply in special cases dependent: (*a*) upon the narrowness or the sinuosities of the fjord, which would determine the reach of the waves; (*b*) upon the steepness of the slope back of the ice cliff, which would regulate the different velocities of surface

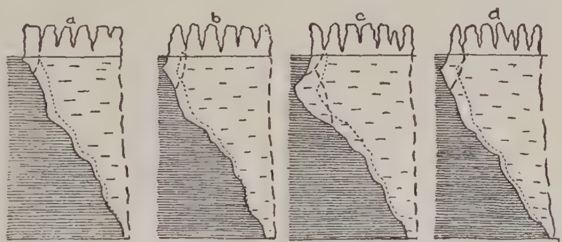


FIG. 98. — Supposed successive forms of a tide-water glacier front (after Reid).

and bottom layers of ice, and determine the measure of crevassing; (*c*) upon the irregularities in the floor of the ice tongue, which would largely fix the amount of shearing and overthrusting; (*d*) upon the presence or absence of warm ocean currents, which would regulate the rate of melting of the ice by the fjord water; and (*e*) upon the freezing of the water surface,[6] which must put a bar upon the action of the waves during the colder period.

**Studies of Bergs Born of the Inland-ice of Greenland.** — Though ice bergs are discharged from the inland-ice throughout practically the entire extent of the coast line of Greenland wherever inland-ice reaches the sea, yet the great bergs which push out into the broad Altantic arise either

Fig. 99. — A large berg floating in Melville Bay and surrounded by sea-ice.

on the west coast between Disco Bay and Smith Sound, or on the east coast south of the parallel of 68°. To the north of this latitude the bergs are firmly held in the heavy pack-ice, while the bergs of southwest Greenland form for the most part in such narrow fjords that they are too small to travel far before their final dissolution.

The size of the Greenland ice bergs has probably been much overestimated. Of 87 measurements made by von Drygalski on the large bergs calved in the Great Karajak fjord, the highest reached 137 metres above the water, or about 445 feet. This mass of ice was, however, against the glacier front, and probably rested on the bottom. None of the others measured were much above 100 metres high or about 325 feet.[7] The berg shown in Fig. 99, photographed by an earlier explorer in Melville Bay, measured 250 feet in height.

During fourteen months spent in the immediate vicinity of the steep front of the Great Karajak ice tongue, von Drygalski carried out extensive studies upon the calving of bergs, and has distinguished three classes. Those of the third class form almost constantly, and consist of larger or smaller fragments which separate along the crevasses and fall into the sea. Only twice were calvings of the second class observed, namely, in late October and in early November. Of one of these von Drygalski says: —

> I heard a thundering noise, but at first neither I nor the Greenlanders who were with me saw anything. Suddenly a great distance away from the margin of the glacier, an iceberg emerged from the sea, rose out of the water, though not to the height of the cliff, and then moved away accompanied by a continuous loud tumult and by a rise in the level of the water, through the agency of which it moved away from the cliff quite rapidly. It did not come from the cliff, but certainly emerged from below. The Greenlanders, whom I afterwards questioned about it, gave me the same impression. . . . The margin of the glacier was unchanged.

Here it was noticed that the berg was long, though not as high as the ice cliff which terminated the glacier. It is the opinion of von Drygalski that bergs of this class come from the lowest layers of the glacier. Because of the sea-ice which in winter forms in front of the glacier, the ice cliff is at that time not cut away so fast, and it was, in fact,

observed in the winter farther out than during the summer. This explanation in the main is in agreement with that of Russell.

Bergs of von Drygalski's first class, which are the most massive of all, separate from the entire thickness of the ice front. Two such bergs were observed in process of calving by von Drygalski and other members of his party. The same loud sound which had been heard at the birth of bergs of the second class accompanied the birth of those in the first class, *but the movement of separation from the glacier was visible at the same instant.* A portion of the cliff front was seen to separate from the cliff, being thereby thrown somewhat out of equilibrium and started in a pendular vibration which produced great waves in the fjord and increased slightly its distance from the newly formed ice cliff. It was here observed that the main pinnacle of the berg slightly exceeded in height the highest pinnacles of the new glacier rim. This, it will be remembered, is in contrast with the bergs of the second class which did not reach to the height of the cliff. Bergs of the first class usually regain their equilibrium after rhythmic oscillations, and float away in an upright position. The bergs of the second class often turn over, displaying the beautiful blue color of the lower layers. Studies confirmatory of those of von Drygalski have been recently made by Engell,[8] and Salisbury's two types of Greenland icebergs seem to correspond with von Drygalski's bergs of the first and second classes.[9]

The water waves which are sent out to the shores at the birth of a great iceberg extend 50 kilometres or more within the fjord, driving the smaller floating bergs together and thus assisting in their fragmentation and consequent dissolution. The calving of bergs of the first class von Drygalski believes occurs where the depth of the fjord has so far increased that the ice begins to leave the bottom and assume

a swimming attitude. The buoyancy of the water is, he believes, thus the true cause of the separation of the bergs.

Depths which are four to five times as great as the thickness of the inland-ice above the sea level, are not measured in Greenland in front of attached ice masses, because the latter become in that case broken up into ice bergs.[10]

This view gains strength from Salisbury's studies of the glaciers ending in Melville Bay and apparently floated for a very short distance back from their fronts and generally in the middle only.[11]

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# PART III

# ANTARCTIC GLACIERS

## CHAPTER XII

## THE ANTARCTIC CONTINENT AND ITS SEA–ICE GIRDLE

**General Uniformity of Conditions in Contrast with the North Polar Region.** — The essentially reciprocal physiographical developments about the earth's two polar regions are responsible for a striking contrast in their physical, and especially in their glacial conditions. In the north a deep polar sea is largely encircled by a rim of land masses, interrupted, however, in one rather broad area by the northern Atlantic ocean. Nearly opposite this interruption the Pacific pushes a great bay so far to the northward as just to pierce the land girdle. The ridge of the Aleutian arc farther to the south imposes a bar to the movement of ocean currents, and makes the break at this point a less important one than it would at first appear.

The widely different specific heats of land and water, the irregularities of the land surfaces, and especially the large transfer of heat through the medium of northwardly and southwardly directed ocean currents, together bring about a great diversity of climatic conditions within the northern polar regions. Along the same parallel of latitude

the widest differences of temperature and precipitation are to be encountered.

Within the south polar region, on the contrary, the great continental plateau, centred as it is so nearly over the pole and having its borders for long distances so nearly in correspondence with the Antarctic Circle, the surrounding ocean permits of a relatively free circulation of oceanic waters and of air currents. The result is a greater uniformity and a symmetry in distribution of the principal climatic constants with regard to the south pole as a centre. Here the isotherms more nearly follow the parallels of latitude, and, there being a much smaller transfer of heat by ocean currents from tropical regions, the climate is far more severe than within the Arctic regions. For this reason the surface of the sea freezes in considerably lower latitudes, so that the Antarctic continent is encircled by a broad zone of pack ice which offers the most serious bar in the way of those who would explore it.

The uniformity of climatic conditions within the Antarctic we express when we say that its climate is oceanic. To fully understand the severity of this climate it is necessary to emphasize a vital difference between the glaciation of southern and of northern polar regions. Throughout the Arctic regions, with a single noteworthy exception of the Franz Josef archipelago, the snow-ice masses are all smaller than the land areas upon which they lie.[1] Within the Antarctic, on the contrary, the reverse is the case, and *the snow-ice masses quite generally cover all the land surface and push out also upon the sea.* Barring the peninsula of West Antarctica, which sends a narrow tongue northward two degrees or more beyond the Antarctic Circle, land has been seen exposed only in the high Admiralty and Royal Society ranges in Victoria Land, and in a few isolated volcanic peaks, such as Erebus and Terror on the Ross Sea, and the Gauss-

berg of Kaiser Wilhelm II Land. Elsewhere the white snow surface, variously moulded near its margin, is all that meets the eye at the border of the continent.

An oceanic climate is possessed by bodies of land which are surrounded by the sea and are so small that climatic conditions are dominated by the sea rather than by the land. Yet however small the land surface may be, since it is exposed to the sun's rays, it is warmed and cooled more rapidly than is the sea, and in consequence exerts a counteracting influence upon the climate in the direction of a greater changeability. Within the Antarctic, however, where the surface is almost entirely snow-covered, the earth is shielded from solar radiation, and no such influence is exerted. This is an important cause of the difference in climate between the Arctic and Antarctic regions.

**Antarctic Temperatures.** — Nowhere is the uniformity of conditions within the Antarctic region more strikingly exemplified than in the temperatures which prevail and in the small range which separates the winter from the summer temperatures. Thus we find on the margin of the continent at or near the level of the sea and in latitudes near the Antarctic Circle an average summer [2] temperature which is colder than Nansen encountered in the Arctic ice pack within five degrees of the North Pole. Both the average and the extreme winter [3] temperatures are on the other hand as surprising by reason of their moderate values. As illustrating the oceanic climate of Antarctica, we have only to state that the extremes of cold encountered in the Antarctic regions are equalled or exceeded by the temperatures registered at stations south of the 50th parallel in North America. The recent Antarctic expeditions have at last supplied us with reliable data at several widely separated points and for periods of a year or more. These data we have collected and set forth in the following table: —

ANTARCTIC TEMPERATURES IN FAHRENHEIT DEGREES

| Station | Latitude of Station | Longitude of Station | Average Summer Temp. (Dec., Jan., Feb.) | Average Winter Temp. (June, July, Aug.) | Annual Mean Temp. | Minimum Temp. | Authority |
|---|---|---|---|---|---|---|---|
| Snow Hill Island, West Antarctica . | 64° 30′ | 57° W. | 28.13 | −4 | 10.76 | −42.3 | O. Nordenskiöld[4] |
| "Gauss" in the ice pack 50 miles off Kaiser Wilhelm II Land . . . . . | 66° | 90° E. | | | | −29.5 | v. Drygalski[5] |
| "Belgica" in the ice-pack off West Antarctica . . . . | 70–71° 36′ | 85–103° W. | 29.3 | 1.8 | 9.6 | −45.6 | Arctowski[6] |
| Cape Adare, Victoria Land . . . . . | 71¼° | 170° E. | 30.4 | −11.3 | 7.05 | −43.1 | Bernacchi[7] |
| Cape Armitage, Victoria Land . . . | 77¾° | 167° E. | | −15.15 | | −21 | Shackleton[8] |
| Cape Armitage, Victoria Land . . . | 77¾° | 167° E. | | −13.17 | | −17 | Shackleton[8] |
| To the S.E. of White Island on ice barrier near Cape Armitage . . . . | | | | | | −67. (in September) | Scott[9] |

Thus we see that the average summer temperature upon the borders of the Antarctic continent is from two to four degrees below the freezing-point of water, or about the same as the winter temperature of Southern Scandinavia. Passing northward from the Antarctic Circle and beyond the margins of the continent, the rise in temperature is rapid. Thus Bruce's temperature record, taken in the Weddell Sea, gave 7° F. as the lowest temperature reached, while the average summer temperature was near 31.4° F. and the average winter temperature 13.7° F.[10] In the South Orkney Islands, only 3½° farther north than the Snow Hill station of West Antarctica, the average winter temperature is higher by 14° F.[11]

The above described Antarctic temperatures measured

near sea level and on the margin of the continent are, however, quite different from those which are encountered upon the high ice plateau. Data from these levels are naturally only available for brief periods during the summer season. On his trip westward from Cape Armitage over the snow plateau, Scott found that for fifty days the temperature fell almost nightly to $-40°$ F. and seldom rose during the day above $-25°$ F.[12] Shackleton's southern party even in the height of summer nowhere upon the plateau encountered a temperature above 0° F., and temperatures between $-35°$ and $-40°$ F. were often registered.[13]

**Geographical Results of Exploration.** — The wide zone of sea-ice which surrounds the Antarctic continent has been an effectual barrier to navigation of Antarctic waters. If to this we add the remoteness of the region from centres of civilization, and the lack of any lively commercial interest, such as the supposed northwest and northeast passages to the orient in the northern hemisphere, the tardiness of exploration in the south polar regions finds a sufficient explanation. The first important voyage of discovery in that region, that of Captain James Cook in the years 1770 to 1774, was undertaken to solve the problem of the supposed southern continent, the *Terra Australis Incognita.* Cook largely circumnavigated the globe in the latitude of 50° south or more, and for a distance of 115° of longitude kept south of 60° latitude. Three times he crossed the Antarctic Circle, and at one point attained the high latitude of 71° 10′, but without discovering the supposed continent.[14]

It was the importance of the sealing industry in the South seas which some sixty years after Cook's voyages furnished the impetus to the second great period of Antarctic discovery, that of 1838–1841. Three expensive expeditions fitted out in the United States, France, and England were commanded by Wilkes,[15] D'Urville,[16] and Ross[17] respectively.

It is the best commentary upon the difficulties of South Polar exploration that while all these expeditions discovered the Antarctic continent, no one of them succeeded in effecting a landing. With the revival of interest in Antarctica which came after another sixty years had elapsed, during which time strong steam vessels had replaced the earlier sailing ships, Borchgrevink in 1898 wintered at Cape Adare in Victoria Land, and could claim that he was the first to set foot upon the Antarctic continent.[18]

The recent period of Antarctic exploration began, however, with the "Belgica" expedition of 1897–1899, which was assisted by the Belgian government and was commanded by Lieutenant Adrian de Gerlache,[19] though it was soon followed in 1898–1900 by the British Antarctic expedition under Borchgrevink. These two expeditions greatly stimulated an interest in South Polar exploration, and in 1902 three national expeditions wintered in the Antarctic — an English under the command of Captain R. F. Scott,[20] a German under command of Professor Erich v. Drygalski,[21] and a Swedish under Dr. Otto Nordenskiöld.[22] A Scotch exploring expedition commanded by Bruce,[23] and a French exploring vessel under the command of Charcot [24] soon followed. The altogether exceptional importance of the results obtained by the British expedition under Scott led Lieutenant, now Sir Ernest Shackleton, to fit out at his own expense the expedition which for scientific results as well as for an exhibition of fortitude in the face of exceptional difficulties, takes the first rank in Antarctic discovery.[25]

It should not, however, be overlooked that the "Challenger" exploring expedition, while undertaken primarily for other than Antarctic exploration, entered Antarctic waters in 1874, crossed the Antarctic Circle, and has furnished especially valuable data upon the pack and berg ice of that region.[26]

Before the exploring expeditions of 1838 to 1841 had been undertaken, much had been learned from the reports of enterprising seal hunters in the Antarctic, such, for example, as the Englishmen Biscoe, Kemp, and Weddell, and the Americans Palmer, Pendleton, and others. It is certain that as early as 1812 an American sealing station was maintained in West Antarctica.[27] Kemp and Enderby Lands situated in longitude 80–90° W., and upon the Antarctic Circle were discovered in this way and are no doubt continued westward to the point earlier reached by Cook (see Fig. 100).

The expeditions of 1838–1841 were the first which really discovered with certainty the Antarctic continent, though it is now clear that Cook was in 1774 upon its borders. What has been designated Wilkes Land was skirted by Captain Wilkes from about 110° to 145° East in close correspondence with the Antarctic Circle. Here either an undulating high snow surface which Wilkes interpreted as a buried mountain range, or a high ice cliff rising abruptly from the sea, was all that could be made out, and in the fierce storms and almost continual fogs which he encountered, seeing conditions were most unsatisfactory. Ross, Borchgrevink,[28] and Scott [29] have all in turn sailed over the eastern portion of Wilkes Land, and we now know that the coast does not here extend along the Antarctic Circle as was supposed by Wilkes. The Balleny Islands being near the coast as traced by Wilkes, it is altogether probable that in the bad weather which he encountered, these islands were mistaken for the continuation of the Antarctic continent.[30] Von Drygalski has shown how easy it was for Wilkes to have been mistaken in the loom of the continent under the conditions which he encountered.[31] It is now probable that the coast line extends from near Wilkes' Cape Carr in a more or less direct course to Cape North in Victoria Land.

The same coast which Wilkes imperfectly and at great

risk to his vessels charted for 1500 miles, was seen also by D'Urville commanding the French expedition; and on the supposition that the land was seen by him a day earlier than by Wilkes, Scott and Shackleton have each upon their maps replaced the name Wilkes Land by Adelie and Clarie Land, these being the names given by the French commander. It has since been most conclusively shown that owing to D'Urville's failure to drop a day from his calendar when crossing the 180th meridian, his dates are in error, and Wilkes' discovery was really made upon the same day, but some hours earlier than D'Urville's,[32] so closely do the two discoveries of the great Antarctic continent fall together. Sir James Ross, experienced explorer as he was, and in ships specially strengthened for the task in prospect, achieved results of great importance, but was greatly chagrined that he had been anticipated by Wilkes in the discovery of the Antarctic continent, and quite unjustly imputed improper motives to the American commander. He sailed along the coast which he named Victoria Land, with its high range of bare peaks to which he gave the name Admiralty Range, and for 500 miles he skirted the high ice cliff, since generally known as the "Great Ross Barrier" (see Fig. 100).

Since Ross's time three new land areas have been discovered in the South Polar region, while Victoria Land and West Antarctica have been much extended through exploration. The three new land areas are King Edward VII Land, described by the English Expedition under Scott, Kaiser Wilhelm II Land, discovered by the German expedition under von Drygalski, and Coats Land, which was sighted by the Scotch exploring expedition under Bruce (see Fig. 100). Coats Land was found upon Weddell Sea, which, near longitude 20° West, forms a deep indentation in the Antarctic continent nearly opposite the great indenta-

tion of Ross Sea. The question is still open whether these seas may not eventually be connected across the Antarctic

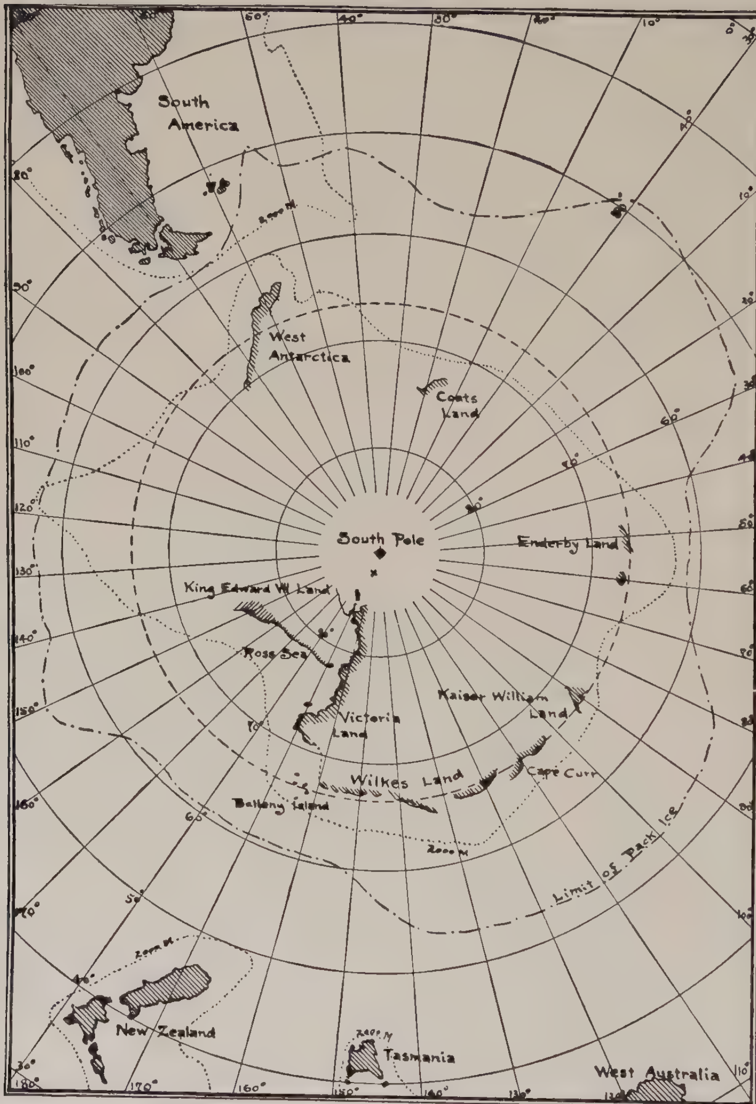



FIG. 100. — Map of Antarctica showing the principal points which have been reached by exploring expeditions and their relation in position to the other continental masses.

barrier ice. Two expeditions, with a view to settle the question, are to-day in prospect.[33]

To summarize, land has now been definitely determined to exist in King Edward VII Land (lat. 75° S., long. 150° W.),

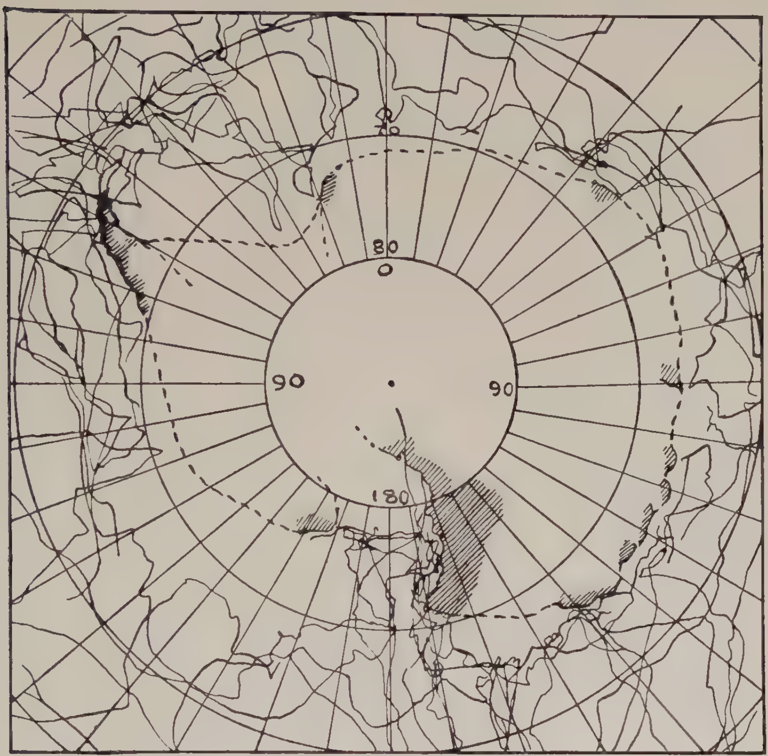



Fig. 101. — Map of the Antarctic regions showing the tracks of vessels. Based on Murray's map of 1894, but brought up to date. The probable outline of the continent has also been indicated, largely in accordance with Murray's view but modified to express later discoveries.

Victoria Land (lat. 70–80° 23′ S., long. 165–170° E.), Wilkes Land (lat. 66½° S., long. 110–150° E.), Kaiser Wilhelm II Land, Kemp, and Enderby Lands (all near the Antarctic Circle and in longitudes 90°, 60°, and 50° E.), Coats Land (lat. 74° S., long. 20° W.), and West Antarctica (lat. 65–70° S.,

long. 60–70° E). The tracks of vessels when charted together (see Fig. 101) have a value by showing where the Antarctic land is proven not to extend.[34] Additional information concerning the continental border may be obtained, even where land has not been seen, through the observation of true barrier ice. Whatever may be the origin of such ice, in all cases where it has been explored, it has been found in connection with land masses, and the supposition is strong that all areas of true barrier ice indicate a connection with land masses. Captain Cook in 1773, when near the Antarctic Circle, and in longitude 40° E., saw a uniform and level mass of ice extending along the horizon, which by imperfect methods he estimated to be 15–20 feet high. This was certainly not pack ice.[35] Biscoe, in 1831, saw at a point somewhat east of Cook's position a perpendicular wall of ice between 100 and 110 feet in height. Again, Kemp, in 1833, at a point still farther to the eastward, discovered Enderby Land, which, so far as he then knew, might be an island, but connected with the discoveries of Cook and Biscoe, and interpreted with our present knowledge, this barrier ice was clearly part of the fringe surrounding the Antarctic continent.

**The Submerged Continental Platform.** — Wilkes was careful to confirm his discovery of the Antarctic continent by a series of soundings which indicated the existence of a submerged platform upon the margin of the continent. Ross obtained off Victoria Land and also near the Ross barrier depths of 100 to 500 fathoms, so that together the observations indicated the presence of a continental shelf, bordering the Antarctic continent in these longitudes.[36] Arctowski,[37] from the soundings taken by the "Belgica" expedition to the westward of West Antarctica, discovered a similar submerged platform, which at its outer edge descended rapidly from less than 300 to more than 1400 fathoms (see Fig. 102). That the platform is at its margin more than twice the usual

depth of continental shelves, Arctowski interprets as evidence of a general submergence of the region. If this interpretation is correct, the amount of submergence is probably even greater than the figures would indicate, for the sound-

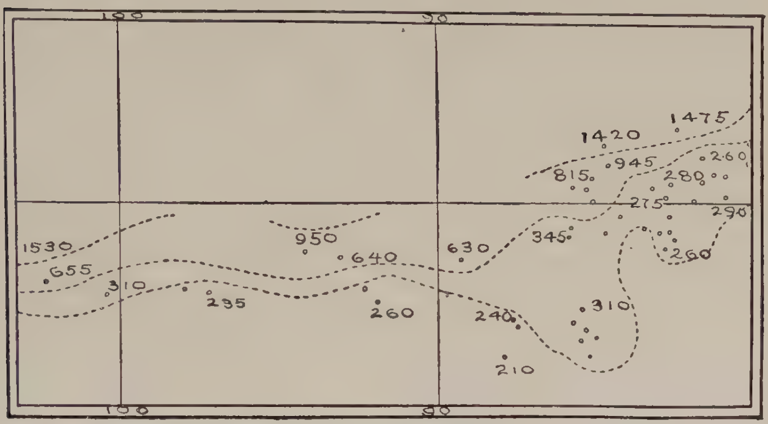



FIG. 102.—Soundings over the continental platform to the westward of West Antarctica (after Arctowski).

ings of the "Challenger" farther to the westward showed that the ocean bottom is there strewn with glacial débris, due, doubtless, to the transporting action of drifting icebergs.[38]

The latest French Antarctic expedition has taken soundings over a portion of the platform examined by the "Belgica," and shown that it is characterized by rather remarkable irregularities of surface. Farther to the westward along the parallel of 70°, and hence outside this shelf, a profound fosse with depths in excess of 5000 metres was discovered, though this decreased in depth to the westward near the longitude of 126° W.[39]

The Scotch Antarctic expedition, when off Coats Land, found the bottom shelving very markedly to depths of 161 and 159 fathoms, which soundings were obtained some two

miles off the land. Then, within a distance of 50 sea miles, the bottom dropped from 131 to 2370 fathoms, thus showing that in this district also the slope bordering the submerged Antarctic platform descends into great depths.[40]

The winter station of the "Gauss" within the sea ice north of Kaiser Wilhelm Land, was over a great submarine plateau, the depths of which, as shown by soundings made while approaching and retiring from the position, ranged from 130 to 375 fathoms. Directly beneath the station stretched a submarine ridge which may perhaps have represented a moraine. On the edge of this platform, the "Gauss" determined the same abrupt descent to considerable depths which had before been found by the "Belgica" farther to the eastward. At points quite near each other, the "Gauss" determined depths of 241 and 2890 metres, and at another place of 382 and 1103 metres.[41] Unlike Arctowski, who assumed a subsidence of the platform to account for its unusual depth, Philippi has interpreted this as evidence that the platform was planed down by the ice from the usual depth of about 100 fathoms when the ice front extended to and beyond the border of the platform. He points out that the general effect of the retirement of an ice sheet is to induce elevation, rather than subsidence.

**The Zone of Sea and Pack Ice.** — The sea ice of the South Polar region encircles the Antarctic continent with outlines roughly parallel to its borders. Sea ice is due to the freezing of the surface of the sea during the winter months. Ross's observations, but particularly those of the "Challenger" expedition,[42] show that a wedge-shaped mass of cold water extends in the sea through about 12° of latitude, the thin northern edge terminating about latitude 53° S. Within this wedge the temperature varies from 28° F. at the thick southern end to 32.5° F. at the thin northern end. The overlying warmer layer of water has temperatures varying

from 32° to 35° F., which represents also the range of temperature of the water below the cold intermediate wedge. During the winter, the warm surface layer is probably absent, and in summer, as already indicated, this upper layer thins toward the south so as to reach the surface at about latitude 65° S.[43] Over the continental platform to the westward of West Antarctica, Racovitza found that the wedge-shaped cold layer of water, here forming the surface, had a temperature of $-2°$ C. ($28\frac{1}{2}°$ F.), and was thickest at the southern end (lat. 31° 7′ S.), and that below this wedge the temperatures increased gradually as far as the bottom, where they ranged from 0° to $-1°$ C. (32° to $33\frac{4}{5}°$ F.). Above this continental plateau the cold water layer is thicker than the warmer bottom layer.[44]

At Cape Adare (lat. 71° 15′ S.) the water of the upper layer remained constant at temperature 27.8° F. ($-1.5°$ C.) whenever the surface was frozen.[45] At Wandel Island during all the cold winter weather while the French expedition was there, the sea water near the surface remained remarkably constant at temperature $-1.7°$ to $-1.9°$ C.[46]

The term "field-ice" in the Antarctic regions applies to the uniform sheet of frozen sea. During the formation of this surface ice, some of the sea salts are squeezed upward through capillary cracks to the surface and there freeze as cryohydrates, which become the nuclei for further growth from atmospheric water vapor. In this way, beautiful rosette-like aggregates of crystals are produced.[47]

The thickness of the sea ice becomes a matter of considerable importance in the study of Antarctic barrier ice soon to be considered, for it is probable that sea ice on which snow accumulates may reach almost any thickness, the ice being forced down below sea level by the weight of the overlying snow. Under favorable conditions this ice is later melted both from the bottom in the water, and from

the surface in the air.[48] This matter will be more fully discussed when the origin of the barrier, or shelf ice, of the Antarctic regions is considered.

Where exposed to the wind, however, snow does not generally accumulate upon smooth ice, in which case its thickness is probably quite moderate. A thickness of $8\frac{1}{2}$ feet is the largest that was measured by the Scott expedition,[49] while 7 feet is the maximum reported by Shackleton.[50] These values were, however, obtained in exceptionally high southern latitudes, and are much in excess of those which have been measured outside of the Ross sea. Thus the greatest thickness measured by Gourdon near Wandel Island was 16 inches.[51]

Not only is the thickness of the sea ice sometimes much increased through snowfall, but when broken up in the spring to form the *pack ice*, some layers are forced beneath others and the whole is frozen into a compact mass of much greater thickness. Thus blocks are built up to form slabs (Schollen ice) which may be 25 feet or more in height.[52]

The cover of sea ice is subject to drift due to air currents blowing over it, and this has special interest. Where explored by the "Belgica" expedition, the coming of wind was foretold by pressures within the ice. It was found that during calm weather there was always a change in the pack accompanied by cracks and open lanes, or *leads*. The pressure is produced afterwards, though before the wind is felt. Still later the wind arrives, and the pressure soon thereafter ceases, when the ice pack is found to be drifting.[53] The pressure in the ice would, therefore, appear to be due to the friction of the wind upon the upper surface near the windward side of the mass forcing that portion forward upon the lee portion, or in some cases against a shore.

This discovery that the principal cause of the crushing within the pack is the distant approach of wind has great

interest in showing that the inertia of rest possessed by such a large body of ice — the excess of the starting friction over sliding friction — induces a tremendous compressive stress within this great ice raft along the wind direction. The wind having exerted its frictional stress over a relatively small area near the distant windward margin, the crushing conditions are similar to those which exist in a long line of freight cars suddenly struck and pushed forward by a powerful engine at the distant end.

The brittleness of ice at low temperatures makes it pertinent to consider these effects of compression within the pack in connection with the well-known experiments of Daubrée and Tresca upon blocks of moulder's wax.[54] A block of this material in the form of a rectangular prism was compressed between the jaws of a testing machine and found to yield by rupture in a network of cracks which were plane surfaces perpendicular to the free surface of the block and arranged within two sets or series, which were approximately perpendicular to each other, though inclined 45° to the direction of compression (see Fig. 103).

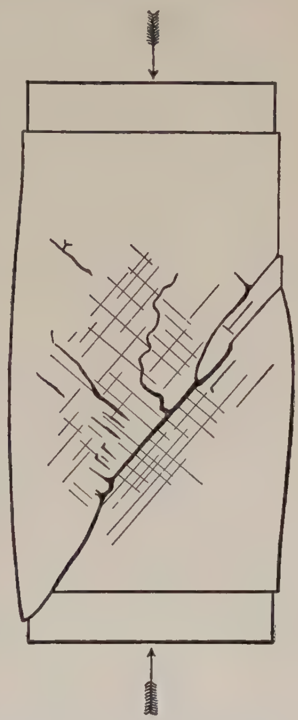


Fig. 103. — Cracks formed on the free surface of a block of moulder's wax when crushed in a testing machine (after Daubrée and Tresca).

Theoretically in a body which varies considerably from perfect elasticity, there would be a larger angle than this with the direction of compression, because of lateral yielding. Test blocks of cement, for example, when similarly tested, show much larger angles between the fracture planes.

Arctowski, as a result of protracted studies upon the ice-pack to the west of West Antarctica, found that the forms of the zigzagging open lanes of water, and the lakes which are found within the pack, are both best explained by assuming the pack to be made up of an aggregation of similar quadrangular elements which compose elements of similar form, but of higher order of magnitude. When the pack is subjected to traction, as by winds passing off its surface, the water leads open in parallel series, first in one and later in another direction, though the larger rafts continue to maintain a quite remarkable constancy of orientation (see Fig. 104).[55]

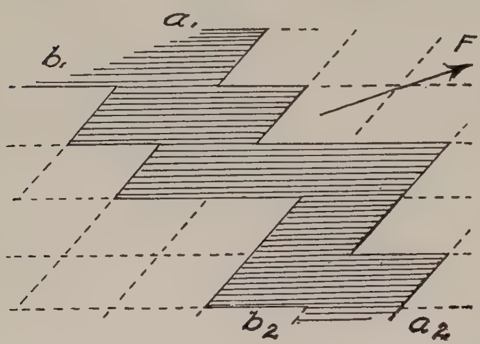



Fig. 104. — Open lane of water within the Antarctic pack ice showing the minor elements of similar form which are believed to be responsible for the zigzagging courses of the water lanes (after Arctowski).

That the neighboring lanes within the pack are essentially parallel was believed to be confirmed by the observation of parallel ribbons of " water sky " in so many cases.

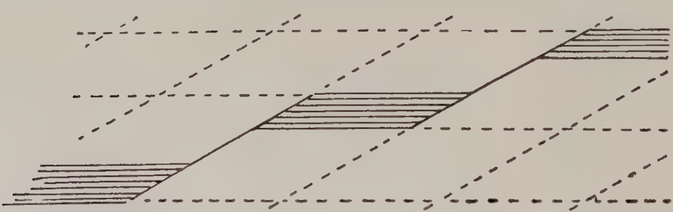


Fig. 105. — Lozenge-shaped lakes within the pack arranged *en èchelon*, and believed to be due to separation and subsequent junction of the pack after a differential shearing motion with reference to the line of rupture, the pack being already divided into lozenge-shaped sections as a result of compression (after Arctowski).

Moreover, the lakes of open water which are found within the pack have quite generally a quadrilateral outline, and could sometimes be seen to have their sides extended by long rectilinear cracks (see Fig. 105).

This tendency of broadly extended ice plates to separate into prismatic blocks is also common to the margin of the shelf ice soon to be considered. A case where half submerged glacier ice has been compressed against an obstructing island and subsequently broken away so as to leave on open strait between, reveals the same vertical fissures and the peculiar zigzags as well.[56]

The thickened sea ice of Posadowsky Bay near its eastern margin has a zigzag outline, and there is found a series of cracks parallel to the northern edge, to which cracks correspond in direction parallel ridges of hummocks and ranks of thickly packed icebergs.[57] This ice is stranded through the icebergs on shallows of the bay, and v. Drygalski believes that the wind friction upon the mass is the direct cause of the phenomena. The outer edge, which is thickened sea ice, changes its position from year to year, new ice being sometimes added to extend the mass, and at other times strips being separated by traction of the wind to float northward with the drifting pack.

While the drifts of the pack in which the " Belgica " was frozen extended through 25° of longitude, its differential motions appear to have been small. The pack and *schollen* ice to the north of Kaiser Wilhelm Land where observed by the German expedition, was notably stagnant, since the " Gauss " maintained its position for many months. Under such circumstances icebergs frozen into the pack maintained their relative positions for long periods, and the snow chased by the wind was arranged in long parallel sastrugi of great perfection (see Fig. 106).[58] Although in both these localities unusually quiet, elsewhere sea ice has been seen to undergo

complex differential, so-called "screwing" movements, which result in the well-known pressure ridges. Some of these form from essentially the same causes as those on the surface of small inland lakes of the temperate regions. During a fall of temperature the ice contracts, thus opening fissures and leads, which in the low temperatures are quickly healed by the formation of new ice. The next rise of temperature with the resulting expansion of the ice, introduces powerful internal stresses which, taking advantage of the relatively weak "planks" of new ice within the fissures, buckles them up into overfolds and overthrust faults. The more important "hummocks" upon the surface of the sea ice result, however, from wind friction upon its surface (see Figs. 107 and 108). Borchgrevink has thus described this phenomenon:[59] —

Fig. 106. — Sastrugi on Schollen ice as seen from a balloon (after Von Drygalski).

Fig. 107. — Pressure lines upon the surface of sea ice (after Shackleton).

In the evening, May 5th, . . . we heard roaring and crushing to the N.W. of our peninsula, and when we came near the beach we witnessed a scene of singular grandeur. The ice-fields were screwing and at the beach the pressure must have been tremendous. Already a broad wall some 30 feet high rose the whole length of the N.W.

beach, and coming nearer we saw that the whole of this barrier was a moving mass of ice blocks, each several tons in weight. The whole thing moved in undulations, and every minute this live barrier grew in height and precipitated large blocks on to the peninsula where we watched the interesting phenomena from the distance of a few yards. The roar of the screwing was appalling.

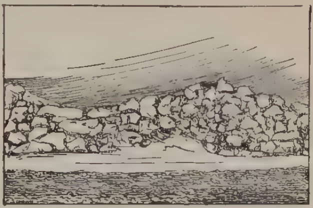


Fig. 108. — Pressure ridge formed on the shore of Victoria Land (after Borchgrevink).

The "Antarctica," returning to Snow Hill Island at the end of the winter in order to take off the Swedish Expedition, was nipped in the pack ice, and its sides yielding to the pressure, it sank so soon as a shift in the pack had released it from its position. This pressure upon the ship was developed suddenly, "the ship began to tremble like an aspen leaf, and a violent crash sent us all up on deck to see what the matter was. The pressure was tremendous; the vessel rose higher and higher, while the ice was crushed to powder along her sides."[60] Later there was a second crash and the ship's sides were crushed in (see Fig. 109).

Fig. 109. — Sinking of the "Antarctica" (after Anderson).

The experiences of the crew of the "Antarctica" after the abandonment of their vessel furnish us the best record of the manner in which the pack is broken up in the spring into

great floes that are carried first in one direction and then in another by the shifting winds. New leads suddenly open at unexpected places, and a little later are as suddenly closed, sending up pressure ridges and hummocks upon the ice surface.[61]

On Ross Sea the gales grow excessively violent towards the end of September and in October (the Southern spring), and by this time the sea-ice sheet has probably commenced to weaken. The general break up of its surface was twice observed by sledge parties connected with the Scott Antarctic expedition.[62] On one day the sea would be seen completely covered with ice, and on the next appear as a clear sheet of open water. Once freed, the ice drifts northward and forms that heavy belt of pack ice which hems in the Antarctic. Inasmuch as the small detached masses of ice move faster than the main sheet, these float in advance upon the north side like a line of outposts, whereas in the south and rear there is a jam with loose pieces crowding hard upon the pack. Amundsen has called attention to a striking contrast between the pack ice of the Antarctic regions and that of the northern hemisphere, due to the more rapid currents in the Arctic seas. While we find in the Arctic ice channels and lakes several miles in length, no similar formations are common in the South Polar region. Amundsen believes that the "indolence" of the ice in which the "Belgica" was imprisoned is explained by the weak currents flowing beneath it.[63]

The manner of formation of the sea ice has been described in some detail among others by Gourdon, who says:[64] —

> With great cold the sea smokes like a furnace because of the great difference between the water temperature and that of the atmosphere. Its surface becomes glistening like that of oil. Minute needles of ice appear, which multiply rapidly and become united into a firm network. The rate of accretion which I have

been able to follow by cutting little rectangles in the ice near the boat is very rapid during the first hours of its formation. The thickness often attains 6 to 7 centimeters (2¼ to 3 inches) in a few hours. After that the increase goes on more and more slowly. The first beds formed are an insolator which protects the subjacent water, so that to attain a thickness of 12 to 15 centimeters (5 to 6 inches) requires several days. The ice of the first hours has a platy structure, being formed of small lamellæ which imprison between them a little brine. The sea water in freezing throws off, in fact, a large part of the salt which it contains; these separated portions having a saline concentration which lowers their freezing point.

. . . . . . .

This ice is pliable and plastic: a thickness of even a number of centimeters undulates with the movements of the swell. If the cold persists, it becomes compact, and with temperatures below −20° C. (−4° F.) it is hard, brittle, and sonorous under the blows of the pickaxe. Its transparency gives it a black appearance in contrast with the snow which covers it.

It is somewhat surprising to note what small thicknesses of sea ice are formed in those cases where no snow has been deposited upon the surface. This has now been learned on the basis of discoveries by Nansen, Peary, and others within the Arctic regions. The greatest thickness measured by Gourdon near Wandel Island was a little in excess of 16 inches.

Thus sea ice differs from lake ice in that it does not form in vertical prisms, as does lake ice. According to Mawson[65] the ice begins to form in scale-like crystals perhaps an inch in diameter, which first float about within a few feet of the surface. Through the motion of the water these scales soon unite to form rosettes, and when they have become sufficiently numerous, these in turn freeze together to form a complete felt-work upon the surface. In this initial stage of the ice cover, the ice is dark and partially transparent, as well as peculiarly flexible. If there be a heavy swell, this cover is broken into pieces a foot or more in diameter, depending

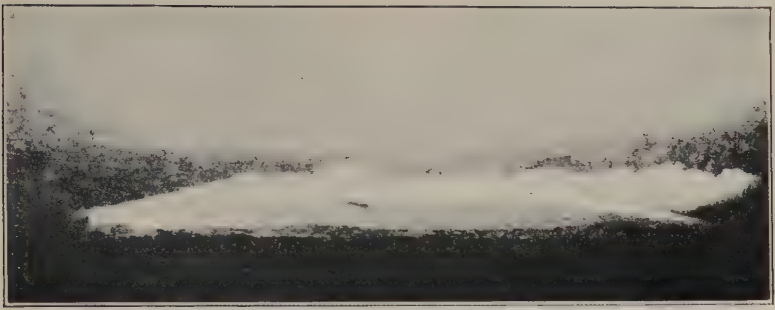
upon its thickness at the time, and these cakes by jostling together become rounded and turned up at the edge — the well-known "pancake ice."[66] Eventually, when the cakes are again frozen together, a stronger cover is produced which increases in thickness through the growth of vertical ice prisms upon its lower surface. These prisms may be a half inch in diameter and many inches in length. Snow falling upon the surface of ice increases the thickness of the layer, and if continued through more than a single season, the prisms of the lower layers grow upwards through recrystallization. The salt squeezed out of the water during the formation of the prisms remains in white vertical tracts between them.

Upon the landward side of sea or pack ice in contact with the shore, there is generally to be found a fringe of thicker ice known as *shore ice* or as the *ice-foot*. This foot usually rises to a height of 6 to 10 feet above sea level and has the form of a flat, narrow terrace 20 to 100 feet wide (see plate 27 B). Sometimes, however, it shows a cliff 80 to 100 feet high with a summit ascending inland in a more or less steep snow slope. The ice-foot may have been formed either by the freezing of the sea water which dashed as spray against the cliff, in which case there are beautiful ice caves lined with stalactites, but it is generally the result of a collection of snow in the form of a drift under the lee of the cliff.[67] If formed either wholly or in part from snow drift, the ice-foot is apt to have alternate layers of compressed snow and of sand and gravel, both alike the work of the fierce southerly blizzards. The sea ice, which moves up and down with the tides, which on Ross Sea have a range of from two to three feet, is usually separated from the shore ice or ice-foot by one or more well-marked "tide cracks."

**The Ice Islands and Ice-foot Glaciers.** — The low islands in high southern latitudes are always snow-covered, so that no

*A.* Fringing glaciers about Sturge Island, Balleny Group (after Scott).

*B.* Ice-foot with boat party landing (after Scott).



*A.* Ice-dome on Bouvet Island (after Chun).

*B.* Névé stratification in ice island (after Arctowski).

land is visible [68] — the land is entirely enveloped in an ice-cap (see Fig. 110). Such islands from a half mile to a mile or more across are found to the northward of King Edward Land.[69] Even in the low latitude of 54° the volcanic Bouvet Island was sheathed in snow when visited by Krech in

FIG. 110. — Ice island off King Edward Land (after Scott).

midsummer.[70] The clouds but partly conceal the perfect shield form of the island in the view of plate 28 A. Similar ice islands have been described by Arctowski.[71] Where these come down to the sea, the ice cliff shows the characteristic névé stratification (see plate 28 B).

Where the islands are higher, the snow either wholly or in part is blown by the wind from the higher surfaces into the lee of the hills and thus forms a fringing zone of ice-foot. Such a fringing ice-foot is illustrated by Sturge island of the Balleny Group to the north of Victoria Land (see plate 27 A).[72] The ice-foot surrounding a land mass represents a type of fringing glacier not unlike those described by Chamberlin and Peary from Northern Greenland.[73] For long distances these marginal bands of rather steeply sloping snow and ice bound the elevated land and have in consequence been called by Otto Nordenskjöld *ice-foot glaciers*. They are obviously built up from drift snow and have a definitely stratified structure.[74] These ice-foot glaciers are what Arctowski has described as slope glaciers (*Gehängegletscher*),[75] and Gourdon as "piedmont" glaciers.[76]

Upon the larger islands of West Antarctica there are

found thin bodies of inland-ice through which the rock peaks project as nunataks. This type of southern glacier resembling as it does some of the ice-caps of Spitzbergen has been designated by Otto Nordenskiöld the *Spitzbergen type*.

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[27] This small area of land, or some portion of it, has received so many names that it seems well to avoid confusion by adopting the one general term which is without international significance. The names Dirk Gerritz Archipelago, Graham Land, Palmer Land, Danco Land, Alexander I Land, and King Oscar II Land recall respectively Dutch, English, American, Belgian, Russian and Swedish affiliations connected with discovery.

[28] Borchgrevink, l. c., pp. 55–57, 2d map at end of volume.

[29] Scott, "Voyage of the 'Discovery,'" vol. **2**, pp. 390–393. Chart in cover.

[30] It is clear from the reading of Wilkes' narrative that the term "icy barrier" which he repeatedly employs should not be interpreted in the technical sense which it has since acquired. While in many cases it clearly refers to true barrier ice, it is none the less evident from the language used that in other cases pack ice only is referred to.

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[34] For a large-scale map showing tracks of vessels to 1905 see H. R. Mill, "The siege of the South Pole," London, 1905, chart at end.

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[50] T. W. E. David, in App. II of Shackleton, l.c., vol. **2**, p. 277.

[51] Gourdon, l.c., 1908, p. 125.

[52] Racovitza, l.c., p. 417.

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# CHAPTER XIII

## THE MARGINAL SHELF-ICE

**Its Nature and Distribution.** — The so-called "barrier" ice, such as was without doubt seen by Cook in 1774, offers one of the peculiarities in which the South Polar area is sharply differentiated from its antipodal region. Nowhere within the Arctic regions is there found to-day anything which in any degree can be compared to the Antarctic barrier ice. Until the British Antarctic Expedition of 1901–2, the origin of this ice was a complete mystery, and even to-day widely different interpretations have been offered. There is, however, every reason to believe that during the period of Pleistocene glaciation, similar ice masses occupied the Gulf of Maine in Northeastern North America as well as the borders of the continent of Greenland and of Patagonia. It is this fact, especially, which lends unusual interest and importance to the study of the existing barrier ice of the Antarctic regions.

At the outset it is well to point out that the term "barrier ice" is in every way inappropriate for scientific use, for it suggests merely that this form of ice opposes a barrier to navigation. The term *shelf-ice* proposed by Nordenskjöld [1] is aptly descriptive and will be adopted here. The term "piedmonts afloat" proposed by Ferrar for such masses of barrier ice on the margin of the Ross Sea, has

much to recommend it, but suggests somewhat too strongly the identity in origin with land piedmonts.[2]

As already pointed out, both Cook and Biscoe encountered true shelf ice to the westward of Kemp and Enderby Lands (see ante, p. 196), and though Wilkes uses the term "icy

FIG. 111. — King Edward VII Land, with shelf ice in front (after Scott).

barrier" for obstructing ice of any kind, his descriptions leave us in no doubt that the shelf ice was encountered near Cape Carr in Wilkes Land. The following extracts from his narrative set forth the aspect of this shelf ice as viewed from the sea: —

In some places we sailed for more than fifty miles together along a straight and perpendicular wall from one hundred and fifty to two hundred feet in height, with the land behind it. The ice-bergs found along the coast were from a quarter of a mile to five miles in length.

At 10 o'clock we were not more than three or four miles distant. It appeared prodigious. We saw a cliff with a uniform height of 100 to 150 feet forming a long line westward. . . .

Discovered a high barrier of ice to the northward with ice islands to the southward. . . .

The immense perpendicular barrier encountered yesterday was now in sight trending as far as the eye could reach to the westward.[3]

A year later Ross sailed for a distance of 500 miles along the front of the similar ice wall which has since been named

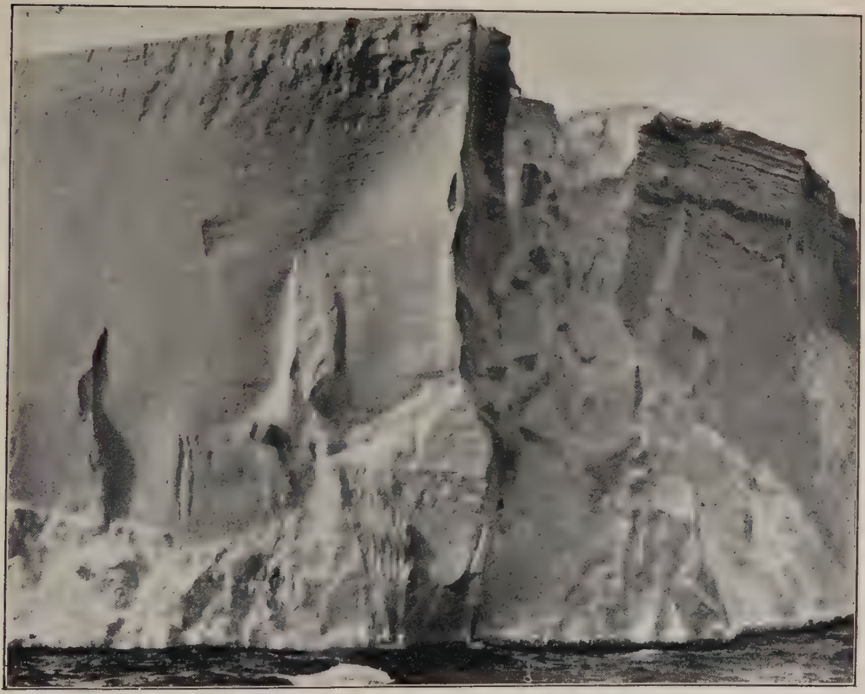
in his honor the "Great Ross Barrier." Within the last decade shelf-ice has been discovered by the Swedish expedition near King Oscar II Land, by the German expedition near Kaiser Wilhelm II Land, by the English Expedition in King Edward VII Land, and by the Scotch Expedition in Coats Land. The first two districts having been examined in some detail upon the spot, will be more fully discussed below under separate headings. Of the Coats Land "barrier" it is stated that it formed the terminal face or sea front of the great inland ice [4] (see Fig. 112), which is also

Fig. 112. — The *Scotia* off Coats Land, the shelf ice showing to the right in the middle distance and also in the distance (after Bruce).

true of the shelf-ice of King Edward VII Land. (See Fig. 111.)

**The "Great Ross Barrier," Victoria Land.** — In 1840 Sir James Ross skirted for a distance of 500 miles an ice cliff which according to his estimates had an average height of 165 feet. The next visit to this ice wall was made in 1899 when Borchgrevink sailed for some distance along its front,[5] and in 1902 Scott made a detailed survey of its entire length (see Fig. 113).[6] The appearance of

*A.* The margin of the Great Ross Barrier (after Scott).



*B.* Near view of the Great Ross Barrier where highest, 280 feet (after Scott).

this mighty ice cliff as seen from the sea is brought out to advantage in Plate 28 A and B. The height when observed from a short distance appears remarkably uni-

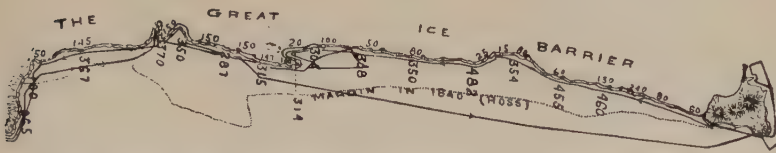



FIG. 113. — Map of the Great Ross Barrier showing heights of the cliff in feet and soundings of the sea in fathoms. Full line is track of "Discovery" (after Scott).

form, though on approaching nearer it is seen to vary from 50 to 280 feet, and in places is even lower than the minimum figure given. Scott mentions a locality where the ice face is so low that one could step from the rail of the "Discovery" directly on to the summit of the barrier.[7] (See Fig. 115 *a*.) A higher edge is represented in Fig. 115 *b*, in which the "Discovery" is seen against the ice cliff within a narrow cove of the ice margin.

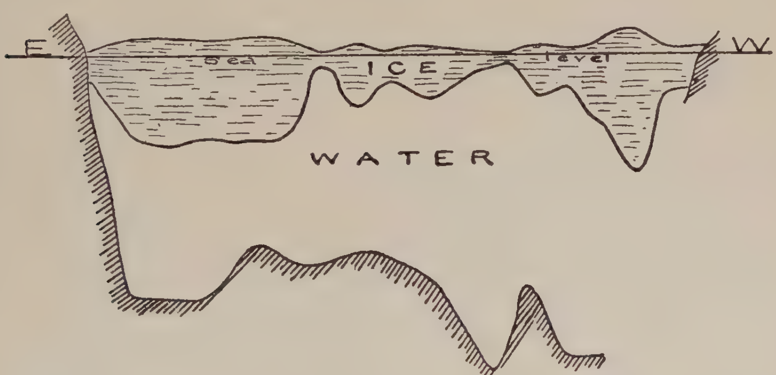



FIG. 114. — Section along the Ross Barrier edge based on Scott's figures and showing the underlying water layer upon the assumption that the submerged and emerged portions of the ice are in the ratio by volume of 5 to 1.

Examination of the perpendicular face of the Ross Barrier shows clearly that its structure is quite different from

that of true glacier ice. It is an immensely thick formation of snow horizontally stratified. Even at a great distance its horizontal upper surface, its vertical fractures, and its dazzling whiteness, all distinguish it from ordinary glacier ice. Studied in detail at different levels, it is seen that pressure has transformed the snow grains into névé snow, the granules of which increase in size and are more intimately interlocked toward the bottom of the cliff. In the upper portions particularly the snow is porous, and hence imprisons a large quantity of air. A study of bergs derived from the barrier which had floated into McMurdo Sound where they were frozen into the sea-ice, showed that except where spray had frozen over the surface they contained no solid ice whatever in the levels above the sea surface. Inasmuch as they were much tunnelled by sea caves, it was possible to follow the study well into the interior. Everywhere, however, they showed only compressed snow.[8]

The specific gravity of the shelf ice must as a consequence be much below that of true glacier ice, so that the barrier, if afloat, should float relatively high. Scott estimates that fully one-fifth of the mass must be above the water surface. Even this proportion may not fairly represent the buoyancy of shelf ice, for Captain Evans of the "Nimrod" took soundings around a typical tabular iceberg derived from the barrier, and found that although its height was 80 feet, it was aground in water of the same depth.[9] In this case, therefore, half the mass projected above the water. Off the Ross Barrier, Sir James Ross obtained soundings of 1360, 1800, and 2400 feet,[10] and more recently Scott has shown by soundings that even if one-fifth only of the mass were above the water, there would still be some hundreds of fathoms between its bottom and the bottom of the sea (see Fig. 114). Moreover, since Scott's surveys show that much of

the cliff is to-day twenty to thirty miles farther south than when Ross visited it in 1840, these later soundings are well


FIG. 115 *a.* — Margins of the Ross Barrier on Balloon Inlet, where so low that one could embark directly from the ship's rail.

FIG. 115 *b.* — Where relatively high.

within the border of the shelf ice of the earlier date (see Fig. 113).

Further evidence that the barrier is afloat is derived from the fact that for some distance back from its edge the ice rises and falls with the tide and leaves behind a complex system of vertical fractures as evidence.

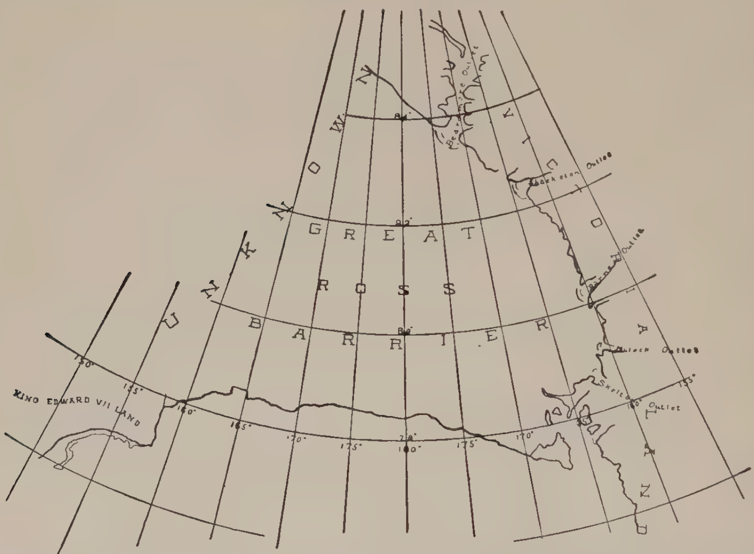



FIG. 116. — Outline map of the known portions of the Great Ross Barrier showing the position of the outlets from the ice plateau (based on Shackleton's map).

Although the Ross Barrier has been crossed by Scott, Royds, and Shackleton for long distances and in one case for over three hundred miles (see Fig. 116), almost the whole mass is believed to be afloat. Soundings not being possible at points within the margin, the best evidence is obtained from its almost perfectly level surface. Scott took aneroid readings at every half degree of latitude along the line of his southern journey, and corrected his readings by comparison with the hypsometer and later with simultaneous readings of the barometer made at the winter quarters near Cape Royds. When thus corrected it was found that the aneroid readings indicated no increase

of elevation toward the South, but on the contrary, a slight and gradual rise of barometer was noticeable such as might be ascribed to the gradual advance toward a fixed area of high atmospheric pressure.[11]

Strong confirmatory evidence for the floating of the barrier is derived also from measurements of temperatures within fissures of the ice. Lieut. Royds found that whereas near the visible land of White Island the serial temperatures in fissures of the shelf ice fell to a mean level of $-9°$ F., at distances of ten miles off the island such temperatures first fell, but at greater depths rose, and at nineteen fathoms (the limit of the test) showed 0° F. This rise in the temperature with depth is best explained through the approach to a water layer beneath the ice.[12]

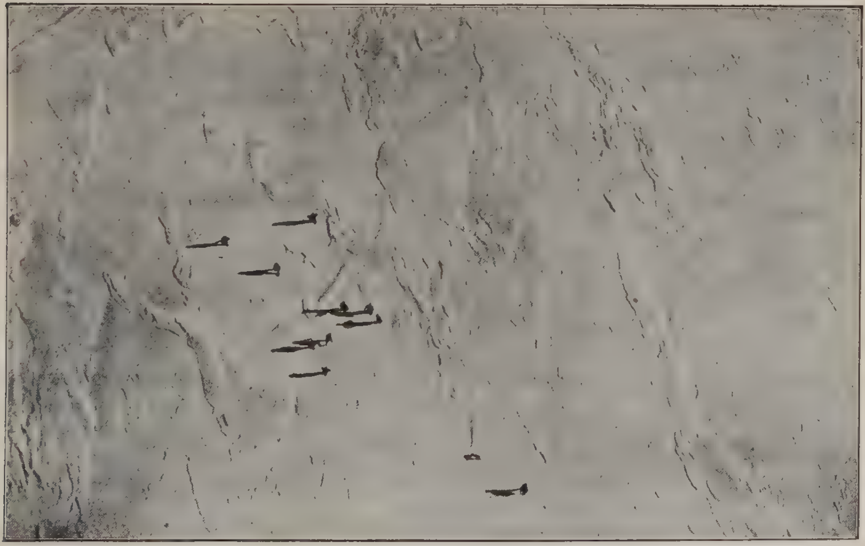
The surface of the Ross Barrier ice, as already stated, is remarkably level. Within narrow limits this is well brought out in plate 30 A and B, which represents photographs of the surface, in one case from a captive balloon. The statement requires modification for those portions only of the shelf ice which approach the continent. In part the Ross Barrier clearly derives its nourishment from the inland plateau ice lying to the south and west. The outlets for this material are great ice streams (one of them fifty miles in width), and so unlike any other known type of glacier that they are deserving of a new and technical name. In the reports of the British expeditions they have been referred to as "inlets" because they offer a possible ingress to the plateau. The term *outlet* would better describe their function in the ice economy, and they will hereafter be referred to by that term. Off these great outlets from the inland plateau ice, the surface of the shelf ice is found to be thrown into long undulations which are recognizable for a distance of twenty miles or more.[13] Elsewhere in the vicinity of the land a similar but narrower zone of disturbance is noticed, which

may generally be followed out from the borders for a distance of ten to fifteen miles. Within these marginal zones the surface of the ice is much crevassed and in striking contrast with its otherwise smooth surface. Similar disturbances accompanied by complex crevassing are observed also about islands which project through the ice nearer to its outer margins. Within a zone immediately adjacent to the mountain borders on the south and west and *within* the disturbed zone, there is a notably smooth ice surface, which is a result of melting through radiation from the rock surface. The ice surface is here in reality that of a frozen lake.[14]

A motion within the Ross Barrier was determined by Scott's party from observations at "Depot A" near Minna Bluff seventy-five miles or more from the cliff edge. Here during a period of $13\frac{1}{2}$ months the movement was 1824 feet in a direction a little to the east of north or toward the barrier edge. This corresponds to an annual rate of something over 1600 feet. The determination came about through an accidental rediscovery of the station; but even more important, the depot was again rediscovered and relocated by the Shackelton party after another interval, this time of over six years. The movement during this interval amounted to 9600 feet, or about 1500 feet per year, in a direction east-northeast.

This important verification of the earlier determination that the shelf ice of the Ross Barrier moves at a rate of more than four feet per day, or nearly four times as fast as the edge of the inland ice of Kaiser Wilhelm Land,[15] must certainly be accounted of the greatest importance. If its cause is the contribution of plateau ice furnished through the outlets along its borders, the ice in these must either have a very rapid movement or be exceptionally important at points beyond where exploration has been carried to

*A.* Horizontal surface of the Ross Barrier, to the south of Minna Bluff, with sastrugi (after Scott).



*B.* View of surface of Ross Barrier taken from a captive balloon, showing sastrugi. The black spots are men and the long dark lines their shadows (after Scott).

*A*. A new ice-face on the Ross Barrier (after Scott).

*B*. An old ice-face on the Ross Barrier (after Scott).

the south of the Beardmore outlet. The possibility is not excluded that the Ross Barrier is directly connected with the shelf-ice at the head of the Weddell Sea on the opposite side of the pole, and that drift sets in the direction of the former.

Although the shelf-ice is unquestionably in part nourished by the outlet glaciers leading down from the ice plateau to the south and west, it is itself a vast névé, as has already been shown from study of its structure, and account must, therefore, be taken of alimentation from the snow falling upon its surface.

The annual snow fall at Depot A, about seventy-five miles from the barrier edge, is equivalent to $7\frac{1}{2}$ inches of rain. Though usually reckoned as the equivalent of as many feet of snow, the snow is here so compact as to possess less than twice the volume of the equivalent water (or $13\frac{1}{2}$ inches).[16] At Cape Royds, the winter station near the barrier edge, the annual snow fall was estimated on the basis of measurements as the equivalent of $9\frac{1}{2}$ inches of rain. These figures, however, like those obtained at Depot A, include drift snow, and there is no means of telling what proportion of the total was locally derived and what was brought from a distance by the winds. Although still heavier falls are assumed for the Drygalski ice barrier tongue to the northward, it should be noted that at Cape Adare where the likelihood of collecting drift is comparatively small (lat. 71° 15′ S.), the snow collected by the gauges of the Borchgrevink party during an entire year was equivalent to but 3 inches of rain.[17]

Whether from drift or from local precipitation, the effect of snow in nourishing the shelf ice is much the same, and it is estimated that on the average about one foot of heavy snow is each year added to the surface of the Ross Barrier. If the contribution of the ice from the Beardmore outlet be

estimated to have moved toward the barrier edge at the uniform rate of about one-third mile annually, before it could have covered the 300 miles separating the outlet from the present margin, some 900 years must have elapsed, and during this time this glacier ice will have been buried beneath some 900 feet of compact snow as measured at surface density.[18] The true glacier ice derived from the outlets is, therefore, not to be looked for in the shelf ice except in the submerged portions where direct observation has not yet gone. The upper and visible portion of the Ross Barrier is hence in all probability throughout of local derivation and is properly regarded as névé snow.[19] Some confirmation of these conclusions is derived from the study of the structure of Antarctic icebergs, which after partial melting, or after overturning, bring the bottom layers to the light of day (see below under Icebergs).

**The " Higher " and " Lower " Ice Terraces off King Oscar Land.** — The Swedish Antarctic expedition of 1902 encountered large areas of shelf-ice in most respects resembling that of the Ross Barrier. This was met on the long sledge journey of Nordenskiöld and Sobral in a direction west-southwestward from the winter quarters at Snow Hill Island. After eight days upon the sea-ice of Larsen Bay and when near the Seal Islands (see Fig. 117),[20] a high ice wall suddenly appeared across their path. This wall was ascended over the sloping surface of a snow drift banked against it, and the course was laid over " an even plateau destitute of fissures." Once only, a faint depression was noted from which the land could not be seen. Near the marginal cliff of this " lower " terrace a few lava islands projected through its surface, and here alone smooth ice cracks or pressure ridges were encountered. After travelling about 100 miles over the surface of this " lower " terrace, the land was approached, and for the first time, the surface appeared broken by numer-

ous crevasses so deep and broad as effectually to block further passage in that direction.[21] Here there rose a second terrace of ice going out from the shore of King Oscar Land and extending in a nearly straight line toward the east until it


FIG. 117. — Map showing the "higher" and "lower" terraces of shelf-ice near King Oscar Land (after Nordenskjöld).

was lost in the horizon. In contrast with the "lower" terrace this "higher" terrace was broken into numberless fissures.[22] Nordenskjöld's belief is that the shelf-ice (the "lower" terrace) is in the main nourished through the precipitation and gradual accumulation of snow upon the surface of sea-ice above a shallow sea. Over the ice of Larsen Bay the sledging party had found in October a thick layer of snow covered by a light crust, through which the ice-axe

could be driven to the depth of a metre. As the snow layer upon the ice deepens, and the underlying sea-ice is by its weight more and more depressed toward the shallow bottom, the warming effect of the water would gradually decrease, and the snow layer in consequence would increase in thickness at an accelerated rate.[23]

It is strongly emphasized by Nordenskjöld that in this accumulation of the snow the wind plays a larger rôle than local precipitation. On the Snow Hill Island ice-foot the surface was raised a few centimetres only during the winter, whereas it increased fully thirty centimetres during the summer. It should be borne in mind that the summer months have air temperatures corresponding to those of winter in lower latitudes (about 1° F. in the warmest month), and more snow is precipitated during the summer months. This snow is, moreover, softer, and adheres more readily to the surface on which it is deposited. Still further, the winds during the summer months are upon the average only about half as strong as during the winter. Wherever protected from the wind snow accumulates, so that small islands are covered, and the ice-foot glacier pushes out from the margins to be extended in the form of shelf-ice.

Valuable data bearing upon this point are also being supplied from a different quarter. Mr. J. B. Tyrrell during many winters spent about the fresh water lakes of Canada, has found that if snow falls to a considerable depth soon after the ice has first formed, this load will press the ice down into the water. Young and flexible ice will bear up less than its own thickness of the dense snow of the Canadian wastes. With the greater thicknesses which are common, the ice is bent down and water rises through fissures so as to wet the lower snow layers. With severe weather this wet snow is frozen and the ice thickened from the upper surface.[24]

We have seen that the Scott, Shackelton, and Nordenskjöld expeditions are practically in agreement as to the importance of local snow deposition in the alimentation of shelf ice formations. Nordenskjöld would ascribe both the origin and growth of the shelf ice of West Antarctica to this cause, whereas Scott regards the Ross Barrier as the relic of a much larger area of ice shelf which once filled all of Ross Sea and rested throughout upon its floor. This view of the former extension of the Ross Barrier is, as we shall see, abundantly supported by evidence. Of great importance is the comparison of the barrier margins of 1840 and of 1902 (see Fig. 113), since during a period of sixty years this wall has retired in places from twenty to thirty miles.

**The " West-ice " of Kaiser Wilhelm Land.** — To the west of Posadowsky Bay and westward and northward from the inland ice of Kaiser Wilhelm Land, lies a dead mass of ice which the late Professor Philippi regarded as true shelf-ice, and which in the main may be compared to that of the Ross Barrier.[25] Owing, however, to the different opinions which have been expressed concerning its origin, this area of stagnant ice has been given the colorless designation " West-ice." Unlike the Ross Barrier, with which the West-ice has been compared, it has a blue color, and as already mentioned, it appears to be stagnant, since no evidences of disturbance have been found at either its sea or its inland-ice margins. Unlike the Ross Barrier, also, it lacks the smooth surface of that body, where it has been explored. For the most part, its surface is very uneven, and might even be described in places as chaotic or labyrinthine. In its northeastern portion it is traversed by deep rift-like valleys, which led von Drygalski to believe that it is constituted of a group of closely crowded icebergs more or less welded together and with the intervening passages partially healed by the indrifted snow. He has, however, referred to the West-

ice as similar to the shelf ice of Ross Sound and West Antarctica.[26]

Seen from the sea when the "Gauss" skirted its front, the West-ice showed a high perpendicular wall in all respects

Fig. 118. — West-ice seen from the "Gauss" off Kaiser Wilhelm Land (after von Drygalski).

resembling the cliff faces of the other bodies of Antarctic shelf ice (see Fig. 118), and this wall was followed through three degrees of longitude. The eastern portion of the mass, which was examined by sledging parties, pushes its margin out to the northward and ends in three great ice tongues separated by bays and terminating in steep cliffs. These

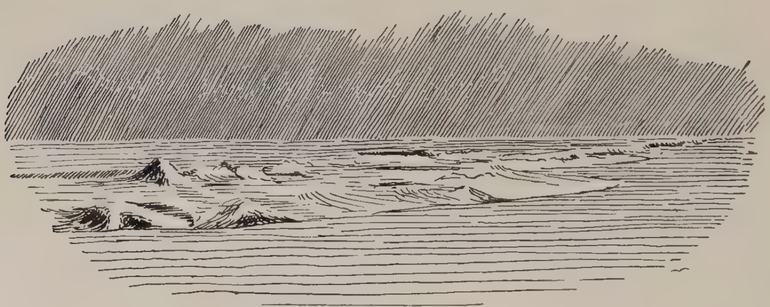


Fig. 119. — The junction of the West-ice and the sea ice (after von Drygalski).

cliffs at the different localities that were visited varied in height from fifteen to sixty-five feet. Locally drifts of snow formed sloping bridges down to the sea ice (see Fig. 119). Both sea and shelf ice rose and fell together with the tides, since no tide cracks were observed to separate them. This indication that the West-ice is afloat was confirmed through

the absence of any ice-foot, as well as by soundings, which showed a depth of water along its borders of six hundred metres. Deep disintegration of the West-ice through melting upon its upper surface was everywhere apparent. Old cracks running parallel to its margin were melted on one side, so that steep cliffs faced northward and formed the south wall of channels for surface streams. Broad trough-like inbreaks led into the mass from its eastern margin, and on one of these the floor had sunk unequally so as to leave the north side high and the south side at a far lower level.

In general, however, the surface of the West-ice is flat with no apparent increase of elevation toward the west and south, though far in the distance along these directions were seen the rising slopes of the inland-ice. That there is to-day no functional connection between the West-ice and the inland-ice has been asserted by von Drygalski (see below, p. 250).

According to von Drygalski, the West-ice is kept in place because of the shallowness of Posadowsky Bay, icebergs being first stranded on the shallows and the intervening lanes being thereafter filled in by drifted snow. While this process furnishes an explanation for the southern or older sections of the mass, the northern or newer portions he believes to have been formed by the thickening of sea ice which has remained in place for a number of seasons. Three north and south bands are made out whose order from east to west appears to be significant in showing the manner of formation of the greater portion of the West-ice mass. The zone to the eastward and on the margin is pack-ice (*Schollenei*s); the middle zone is largely berg ice frozen into a continuous sheet; while to the west the intervening spaces which separate similar fleets of bergs have become either partially or wholly filled in by drift snow, the product

being called "full-ice" (*Volleis*), or, in other words, the West-ice proper [27] (see Fig. 120).

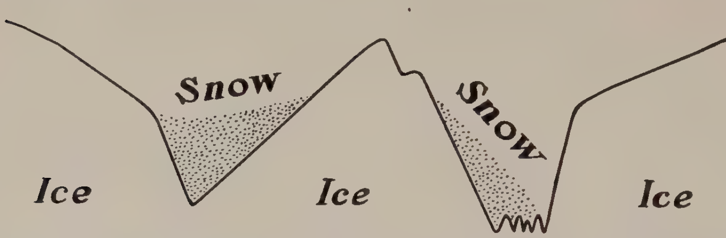



Fig. 120. — Diagram showing manner of formation of West-ice. Eroded icebergs crowded together, cemented by pack-ice and the intervening lanes partly filled in with snow (after v. Drygalski).

**The Shelf-ice Tongues of Victoria Land.** — Victoria Land has furnished several examples of a new type of glacier ice

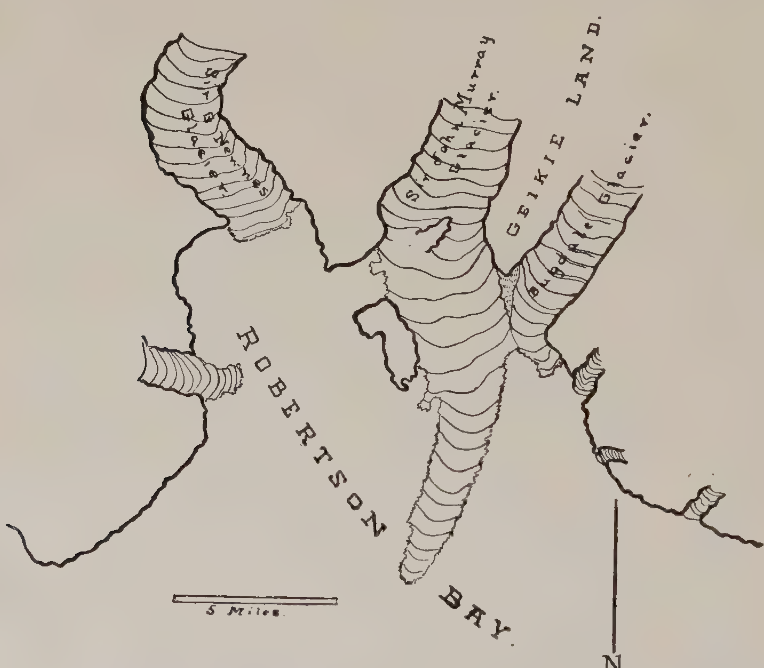



Fig. 121. — Map of the glaciers and ice barrier tongues about the head of Robertson Bay, Victoria Land (after Borchgrevink).

which has interesting relationships to the shelf-ice of the Antarctic regions. It is deserving of a distinct name, and the term *shelf-ice tongue* (ice barrier tongue of the Shackleton expedition) seems on the whole the most characteristic and descriptive. A related form of tongue was first described by Borchgrevink in his map of the Sir John Murray glacier on Robertson Bay, which lies behind Cape Adare in Victoria Land (see Fig. 121). This glacier with the Dugdale glacier descends to the sea below Geikie Land, where it is for some distance wedged in between Duke of York Island and the shore. It pushes out to sea in the form of a long dock, which is 80 feet in height near its margins and rises into the form of one of the dry deltas of an arid region. This form of its surface is of special interest in showing clearly the connection as regards nourishment between the ice of the tongue and the glacier outlet above. From the peculiarities of its surface it would appear to include no true shelf-ice such as is found in the Ross Barrier.

Three large and well marked examples of shelf-ice tongue or "piedmonts afloat" have been reported on by the Shackleton expedition. These are Glacier Tongue, about five miles long and located near the winter quarters on McMurdo Sound, and the much larger Nordenskiöld and Drygalski shelf-ice tongues on the shore of Victoria Land to the west of Ross Sea (see Fig. 122). Smaller tongues of the same type, Harbor and Cheetham shelf-ice tongues, lie similarly at the foot of other but smaller glaciers upon the same shore. Both the Glacier Tongue on McMurdo Sound and the Drygalski tongue to the northward were shown by soundings near their outer margins to be afloat. The Drygalski tongue pushes out some thirty miles from the shore and is more than twelve miles in width. On the basis of soundings it has been thought to be afloat for at least three-fourths of its length, but inasmuch as it rises toward the

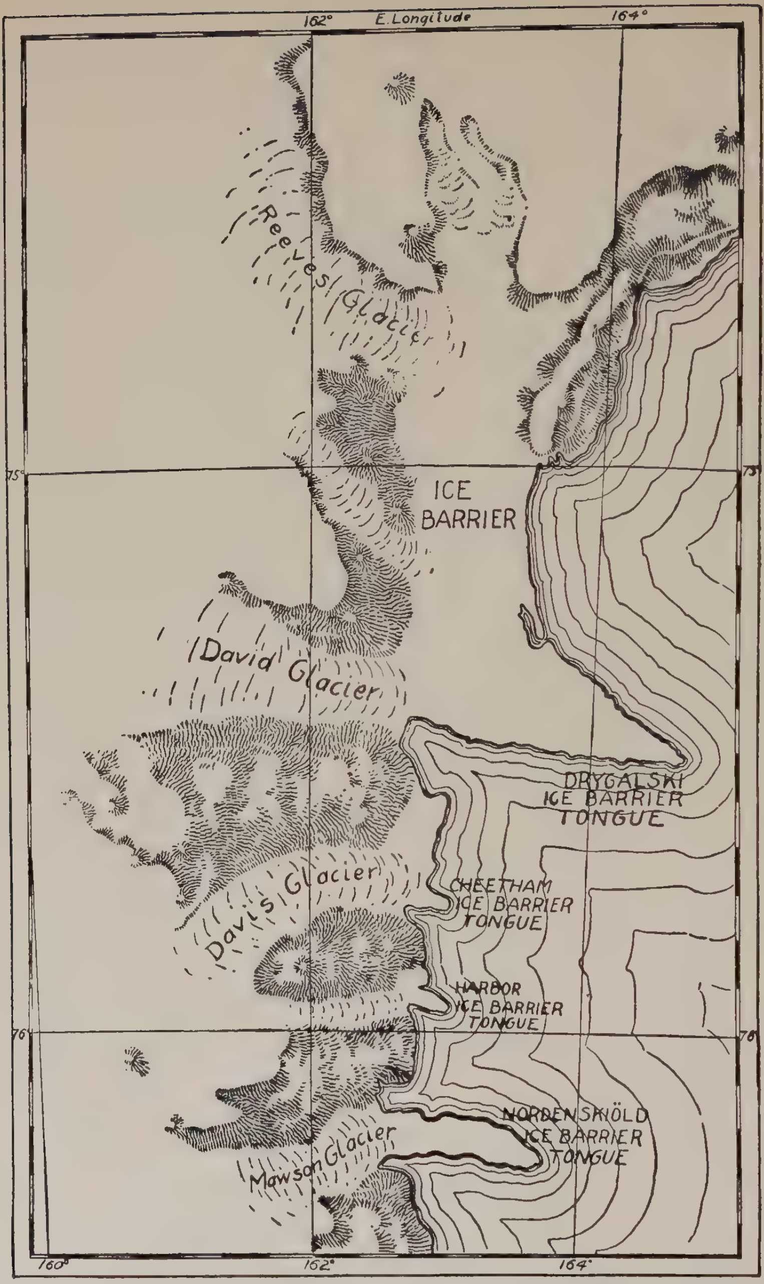



Fig. 122. — Map showing the shelf-ice tongues on the west of Ross Sea with the glacier outlets which descend to them from Victoria Land (after Shackleton).

centre to heights much above its edge, this may be true for the marginal portions only.[28]

The Drygalski ice barrier tongue is clearly nourished from the ice plateau through the great David Outlet, the ice of which raises its shoreward end into a steep and irregular ice apron; but farther out this is "levelled up with snow" and passes into the true flat shelf-ice. At a point only eighteen miles from the shore the marginal cliff was about fifty feet above the water. In all essential respects this tongue appears to resemble that portion of the Ross Barrier which is just below the Beardmore Outlet (see Fig. 134, p. 258), with the exception that the broad extension of shelf-ice is here reduced to a small marginal rim (in the tongue of the Sir John Murray Glacier there is no rim whatever). As there is every indication that the Drygalski tongue is in motion

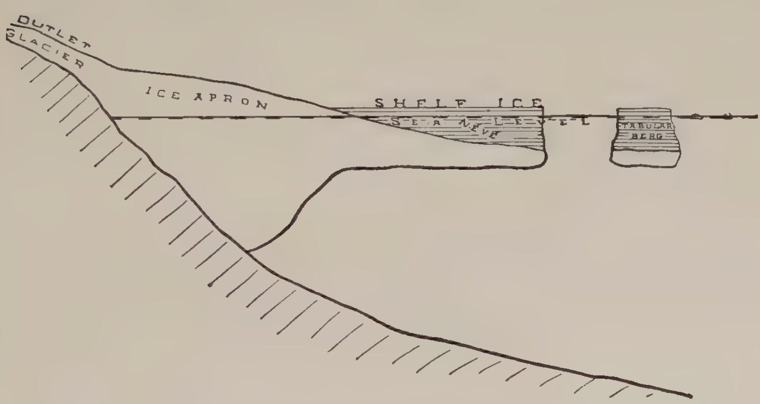



FIG. 123. — Ideal section through shelf-ice tongue showing the apron-like foot of the outlet which feeds it, and the probable pedestal by which it is connected with the bottom and maintained in position. The relation of its glacier ice to the névé of local derivation is also indicated.

and receiving abundant nourishment from the David Outlet, though levelled up with snow near its outer edge, additional light is thrown upon the origin of shelf-ice in general. The probable section of a shelf-ice tongue is represented sche-

matically in Fig. 123. The nourishing glacier raises the surface of the tongue into an apron, and in consequence depresses the bottom of the submerged portion, and being nearest the shore where the water is shallowest, must develop a sort of ice pedestal whose effect will be to stiffen the structure and prevent its being shifted in position. The attenuated form which some of the tongues maintain it would otherwise be difficult to explain.

The Nordenskjöld ice barrier tongue is somewhat smaller than the Drygalski tongue and appears to be no longer deriving nourishment from the plateau ice above. It is thus a relic only of the once larger Ross Barrier, and has additional interest because its southern edge is formed of ice probably originally derived from the Mawson Outlet, whereas its northern edge is of snow forty to fifty feet in thickness brought by the southerly blizzards from the southern side. This is bounded by vertical sea cliffs where slices have been carried away with the sea-ice during the summer. It thus emphasizes the important rôle which wind drift plays in the formation of shelf-ice.

On a portion of the earth's surface where rain is unknown, and where the air temperatures seldom rise above the freezing-point, unfrozen water as a geological agent has an almost negligible importance. In certain localities, however, where the foehn winds are especially strong, such, for example, as the David Outlet, its importance may be considerable. During the weeks of December and January torrents of water rush off the surface of the Drygalski tongue in the form of englacial and subglacial streams. These either cut deep open valleys upon the surface, or tunnel channels under the hard snow and ice.

**The Rectangular Table Berg of Antarctic Waters.** — The normal iceberg of Antarctic seas is as different as possible from the Arctic type, and for reasons which are now suffi-

ciently obvious. In Greenland, true glacier ice descends to the fjord heads, and there gives birth to bergs of blue ice which are limited in size both by the size of the fjord and by the crevasses upon the ice. In the Antarctic, so far as yet known, glacier ice descends directly to the open sea at few points only, but in its place appears the shelf-ice, and tabular bergs separate along broad sea fronts which are measured sometimes in the hundreds of miles (see Fig. 124). The size of Antarctic bergs is in consequence many times greater,

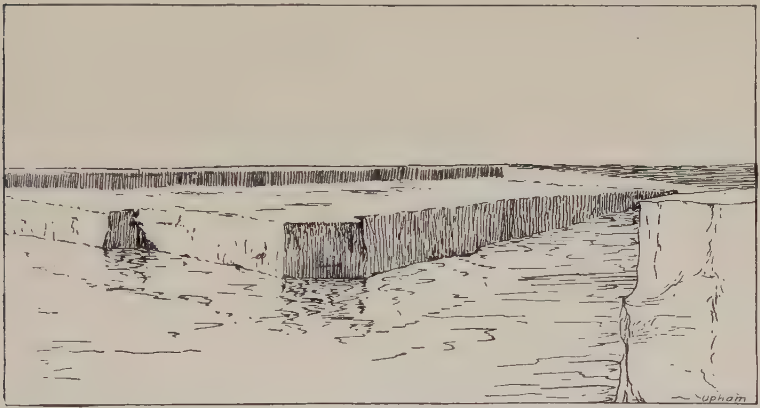


FIG. 124. — The Ross Barrier breaking away to form a tabular and rectangular iceberg (after Shackleton).

and their form is tabular[29] like the ice-shelf from which they have been born (see Fig. 125).[30]

Most of the bergs which were seen in Ross Sea had been derived from the Ross Barrier. They separate from it in great rectangular blocks and leave a relatively smooth vertical face, which later under the action of the waves becomes undercut and more irregular through the separation of small bergs on rectangular joint planes. It is thus easy to determine those parts of the barrier edge which are relatively fresh, and those which have not for a considerable time given birth to a tabular berg (see plate 31, A and B).[31]

Such bergs often show in addition a distinctly terraced structure (see Fig. 126). The term *tabular berg,* which is in common use, is, however, particularly well chosen, because it

FIG. 125. — Rectangular and tabular iceberg of Antarctic waters (after Wyville Thomson).

describes, not alone the smooth horizontal upper surface, but the well-squared rectangular outlines in the plan. Too little attention seems to have been directed to this important fact, to which practically all photographs of Southern icebergs bear witness. It indicates, as we believe, that the shelf-ice at least near its margins is, particularly near the

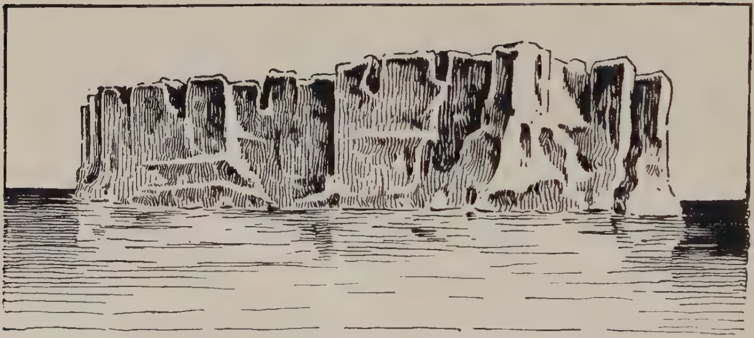


FIG. 126. — Tabular Antarctic iceberg showing perpendicular and rectangular jointing (after Wyville Thomson).

top, generally intersected by vertical joints after the manner of horizontal bedded and compact rocks (see Figs. 126 and 127).[32] Such joints appear indeed in many views and might perhaps be explained in part by the torsional strains set up by the tidal movements — not unlike those described in the well-known experiments of Daubrée.[33] References to this jointed structure are, however, seldom met with in the liter-

ature, but those of the "Challenger" reports are sufficiently clear:[34]—

FIG. 127. — View of a tilted tabular iceberg showing the rectangular lines of the plan (after Wyville Thomson).

Nearly all of the flat-topped bergs showed numerous crevasses in their cliffs near their summits, and these were always widest towards their summits, and were irregularly perpendicular in general direction.

. . . . . . .

The stratified structure of the bergs is best seen in the case of the flat-topped rectangular bergs, where an opportunity is afforded of examining at a corner two vertical cliff faces meeting one another at a right angle.

. . . . . . .

Cliff surfaces, where freshly fractured, showed an irregular jointing and cleavage of the entire mass, very like that shown in a cliff of compact limestone.

Gourdon of the late French expeditions to the Antarctic refers to such bergs as "absolutely prismatic at their birth."[35] Descriptions of the structure of Southern icebergs have much in common with those of the Ross Barrier, save only that they reveal near the bottom especially the presence of blue ice layers intercalated in the white.

According to Arctowski the tabular icebergs which he saw to the west of West Antarctica are névé near the top, while the alternate blue and white bands appear only near the base. Both these latter have the granular structure of névé ice.[36]

Wilkes reported icebergs which were from fifty to two hundred and fifty feet in height with definite strata, of which thirty were counted in the smaller bergs and eighty in some of the largest, the average thickness of the layers being about two feet.[37] Wyville Thomson says of such bergs that "the entire mass shows a well marked stratification, being composed of alternate layers of white, opaque-looking, and blue, more compact and transparent ice."

. . . . . . .

> Towards the lower part of the cliffs, the strata are seen to be extremely fine and closely pressed, whilst they are thicker, with the blue lines wider apart in proportion as they are traced toward the summits of the cliff. In the lower regions of the cliffs the strata are remarkably even and horizontal, whilst toward the summit, where not subjected to pressure, slight curvings are to be seen in them corresponding to the inequalities of the surface and the drifting of the snow.[38]

This presence of blue layers was not, however, observed in the icebergs near the great barrier itself.[39] This, as well as a thorough study of the barrier edge, makes it probable that the icebergs studied by Wilkes and Thomson outside the Arctic Circle were derived from some other masses of Antarctic shelf-ice, which on the basis of their observations must contain blue ice layers. The definite separation of the bergs into thick white layers near the top with thin intermediate blue layers only, and the concentration of the latter toward the bottom, where pressure has removed the air from the more porous white layers, gives the strongest confirmation to the views of Reid and Hess [40] based upon

observations on mountain glaciers, that the blue veins separate the annual snow deposits of the névé.

Speaking of the stratification in Southern icebergs, von Drygalski says:

> Without doubt it is similar to original névé stratification, only that this in the South occurs down to the sea level, because no separation exists between regions of alimentation and removal. The clear layers are those which for a long time (not necessarily annual periods) have lain on the surface without new piling up of the snow. They are either melted by the sun's rays, and thus hardened, or subjected to pressure and rendered firmer by the wind. Between them there are more porous layers which appear as the white ones in the stratification and are characterized by a greater content of air.[41]

To test the different properties of the white and blue portions of a berg, two twelve-pound shots were fired from the "Challenger," one at the blue lower layers, and the other at the white upper zone. The first splintered the relatively hard and brittle blue ice, leaving conchoidal surfaces, while the second buried itself in the white porous mass.[42] Fragments of the white layer were taken aboard the "Challenger" and being subjected to pressure, were found to be easily deformed, whereas the blue ice, under similar treatment, did not yield.[43]

Southern icebergs of a different type are also formed where the inland-ice comes directly to the sea, with no intermediate barrier of shelf-ice, as is the case in Kaiser Wilhelm Land. The Ross Barrier is not only much the largest well known mass of shelf-ice, but its edge is more than ten degrees nearer the pole than those other barriers which have been merely sighted by navigators. It seems certain that the land of Wilkes Land is relatively near the barrier edge, and this, as well as the climatic differences, might perhaps account for the differences between the icebergs examined by Wilkes and

Wyville Thomson, and those which were seen in Ross Sea and examined by the recent British expeditions. With a narrower barrier, the local névé of the shelf-ice would be relatively thin, so that the glacier ice with its blue layers should be nearer the surface. The studies of Hess appear to indicate that a differential motion between successive layers of névé may account for the development of the blue layers on these planes.[44] There is much need of study of the ice masses in Wilkes Land in order to clear up the relationships of the bergs encountered in neighboring seas.

The drift of the bergs which are born of the Ross Barrier is to the northward, and after passing Cape Adare, to the westward.[45] The icebergs derived from the barriers of Wilkes Land are borne to the westward and the northward. When they have passed the parallel of 65° S. they enter the warm surface layers of sea water and are, in consequence, more rapidly melted in the water, at the same time that the warmer air temperatures reduce their exposed surfaces, transforming them into fantastic groups of towers and minarets.[46]

The surpassing beauty of these partially melted icebergs has been described in picturesque language by Gourdon.[47]

Thus in place of the great regular and prismatic tabular bergs are formed those bizarre and complicated monuments, which recall the ice bergs of the North: towers, pyramids, bell-towers, cathedrals, or palaces, Gothic spires, or Roman porticoes, all styles meet, all architectures touch elbows; for these are forms more strange and unexpected than the most capricious imagination could have dreamed. The whole gamut of blues and greens plays over the walls of these edifices or within the channelings which course about them, and the whiteness of the purest marble does not equal theirs. The transparency of the water permits of following the fairy land of their azure grottoes far below the surface of the sea. During the summer, little cascades fall over their sides, mingling their waters with the waves which break against their glistening flanks; stalactites hang from cornices and capitals.

Under the rays of the sun the ice sparkles with the fire of jewels; their silhouettes take on life in an atmosphere of extraordinary transparency; the warmest colorations invade the sky and are reflected upon the sea, and there are enchanting tableaux which are offered to the eye.

When, however, the sun disappears from the scene, it is a land of death which is presented by these mountains of ice. Soon gathered in great numbers, they resemble the fantastic ruins of a gigantic marble city; in a little while and once isolated, they pass, white phantoms, majestic and silent, into the mystery of the polar mist.

Often before this stage has been reached, they have been deeply tunnelled in sea arches, have been melted unequally, and have lost some of their stability so as to become tilted (see Fig. 127, p. 237), or even overturned.[48] Sir John Murray, who in the "Challenger" had such excellent opportunity to study floating ice, has said of the melted bergs:[49] —

Waves dash against the vertical faces of the floating ice-islands as against a rocky shore, so that at the sea level they are first cut into ledges and gulleys, and then into caves and caverns of the most heavenly blue from out of which there comes the resounding roar of the ocean, and into which the snow-white and other petrels may be seen to wing their way through guards of soldierlike penguins stationed at the entrances. As these ice-islands are slowly drifted by wind and current to the north, they tilt, turn, and sometimes capsize, and then submerged prongs and spits are thrown high into the air, producing irregular pinnacled bergs higher, possibly, than the original table-shaped mass.

Before reaching the 40th parallel of south latitude, the bergs are entirely dissolved. The tilting and overturning which they first undergo, permits of an examination of their under surfaces, and it does not appear that any glacier worn rock débris has been observed in them. The débris of this nature observed in the bottom of the blue icebergs described by von Drygalski and Philippi in Posadowsky Bay, which

are of different origin and derived from the true inland-ice, will be discussed under another section. The fact of importance is that the white tabular bergs have not as yet revealed such materials.

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[10] Quoted by Murray, *Smithsonian Report* for 1893, 1894, p. 358; also ibid., for 1897, 1898, p. 415.

[11] Scott, l.c., vol. **2**, p. 418.

[12] Scott, l.c., vol. **2**, p. 420.

[13] Scott, l.c., vol. **2**, p. 419. David and Priestley, l.c., p. 289.

[14] Shackelton, l.c., vol. **2**, pp. 12–13. Cf. the moats about nunataks (ante p. 169 and post p. 257).

[15] E. von Drygalski, "Die Bewegung des antarktisches Inlandeises," *Zeit. f. Gletscherk.*, vol. **1**, 1906–7, pp. 61–65.

[16] David and Priestley, l.c., p. 287.

[17] Bernacchi, l.c., p. 308.

[18] It should be stated that Mr. Bernacchi, an officer of the Scott expedition, does not accept the view that the Ross Barrier is floating except in the vicinity of its margin, and, moreover, regards it as fed in the usual manner of glaciers — by material which moves down from the higher levels along the southern and western margin (*Geographical Journal*, vol. **25**, 1905, p. 384). Gannett, also, has taken strong exception to the view of partial surface alimentation as above expressed and as advocated by Scott, Shackelton, and David (*Nat. Geogr. Mag.*, vol. **21**, 1910, pp. 173–174).

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[20] Otto Nordenskiöld and J. Gunnar Andersson, "Antarctica, or Two Years amongst the Ice of the South Pole." London, 1905, p. 208.

[21] Otto Nordenskiöld, "Die Polarwelt und ihre Nachbarländer," 1909, pp. 82–84.

[22] Nordenskiöld and Andersson, "Antarctica," p. 220, and map opposite p. 316.

[23] Otto Nordenskiöld, "Einige Beobachtungen, über Eisformen und Vergletscherung der Antarktischen Gebiete," *Zeit. f. Gletscherk.*, vol. **3**, 1909, pp. 326–329. See, however, E. Philippi, "Ueber die Landeis-Beobachtungen der letzen fünf Südpolar-Expeditionen," *Zeit. f. Gletscherk.*, vol. **2**, 1907, pp. 1–21.

[24] J. B. Tyrrell, "Ice on Canadian Lakes," *Trans. Can. Inst.*, vol. **9**, 1910, pp. 4–5 (reprint).

[25] E. Philippi, "Ueber die Landeis-Beobachtungen der letzen fünf Südpolar-Expeditionen," *Zeit. f. Gletscherk.*, vol. **2**, 1907–1908, pp. 9–11.

[26] E. von Drygalski, "Zum Kontinent des eisigen Südens, etc.," p. 439. From this view Philippi has strongly dissented (*Zeit. f. Gletscherk.*, l.c., p. 10).

[27] E. v. Drygalski, "Das Schelfeis der Antarktis am Gaussberg," *Sitzungsber. k. bay. Akad. d. Wiss.*, Math.-phys. Kl., 1910, pp. 1–44, pl.

[28] David and Priestley, l.c., pp. 283–286.

[29] H. Stille, "Geologische Charakterbilder," heft 1, 1910, plates 2–6.

[30] Concerning the ice of Antarctic bergs Wilkes has stated that those encountered along the coast of Wilkes Land varied from a quarter of a mile to five miles in length (l.c., p. 350). Scott has made mention of a berg five or six miles in length, and apparently about as wide, but he states that he saw few which exceeded a mile in length or 150 feet in height. The highest which he observed was measured as 240 feet (Geogr. Jour., vol. **25**, p. 356). Some of the accounts of bergs of exceptional size may perhaps be explained by the assemblage of a number closely crowded together and appearing as one. Such groupings might easily be mistaken for shelf-ice, and no doubt in some cases have been.

[31] Scott, vol. **2**, pp. 408–409, pl. opposite p. 408.

[32] Shackelton, vol. **2**, plate opposite p. 22.

[33] Géologie Expérimentale, 1879, pp. 506–515.

[34] Wyville Thomson, "Challenger Report," Narrative, vol. **1**, 1865, pt. I, pp. 431–432, pls. B. C. D.

[35] Gourdon, l.c., 1908, p. 133.

[36] H. Arctowski, "The Antarctic Voyage of the 'Belgica' during the years 1897, 1898, and 1899," *Geogr. Jour.*, vol. **18**, 1901, p. 374. See also *Pet. Mitt.*, Ergänzungsh., **144**, 1903, pp. 15, 19, 21.

[37] Wilkes, l.c., p. 253.

[38] Wyville Thomson, l.c., pp. 431–432.

[39] David and Priestley, l.c., pp. 287–289.

[40] H. F. Reid, "The Relations of the blue veins of glaciers to their stratification," *C. R.* IX$^{me}$ *Congrès Géol. Intern.*, 1903, Vienna, pp. 703–706. H. Hess, "Die Gletscher," Braunschweig, 1904, pp. 175–178.

[41] E. von Drygalski, "Zum Kontinent, etc.," p. 455.

[42] Murray, *Smithsonian Rept.* for 1897, 1898, p. 419.

[43] Murray, *Smithson. Rept.*, 1893, 1894, p. 363.

[44] Hess, l.c., p. 177.

[45] Wilkes, l.c., pp. 352–353. Scott, l.c., vol. **2**, p. 412. Ferrar, l.c., p. 463.

[46] Wilkes, l.c., p. 351.

[47] Gourdon, l.c., 1908, p. 134.

[48] Scott, l.c., pls. opposite pp. 380, 382, 393, 410.

[49] John Murray, *Geogr. Jour.*, vol. **3**. Reprinted in *Smithson. Report* for 1893, 1894, p. 363.

# CHAPTER XIV

## THE ANTARCTIC CONTINENTAL GLACIER WHERE UNCONFINED

**Inland-ice Margin on Kaiser Wilhelm Land.** — The Antarctic continental glacier, the great body of ice which is supposed to occupy the vast central plateau region of the continent, has been studied in but two districts — Victoria Land and Kaiser Wilhelm Land.[1] Such ice has been more or less indistinctly seen from the sea at a number of points, most recently in Coats Land on Weddell Sea by the "Scotia" expedition. This view is thus described:[2] —

> The surface of this great inland ice, of which the barrier was the terminal face or sea-front, seemed to rise up very gradually in undulating slopes, and faded away in height and distance into the sky, though in one place there appeared to be the outline of distant hills: if so, they were entirely ice-covered, no naked rock being visible.

The ice here reached the sea in a narrow barrier with cliff one hundred to one hundred and fifty feet high, while off its edge the sea was found to have a depth of 940 feet.[3]

It is this type of inland-ice not confined by an encircling mountain rampart which was studied within a very narrow marginal zone by the German Antarctic expedition of 1901–1903.[4]

As seen from the sea, "it was beyond a doubt that the ice

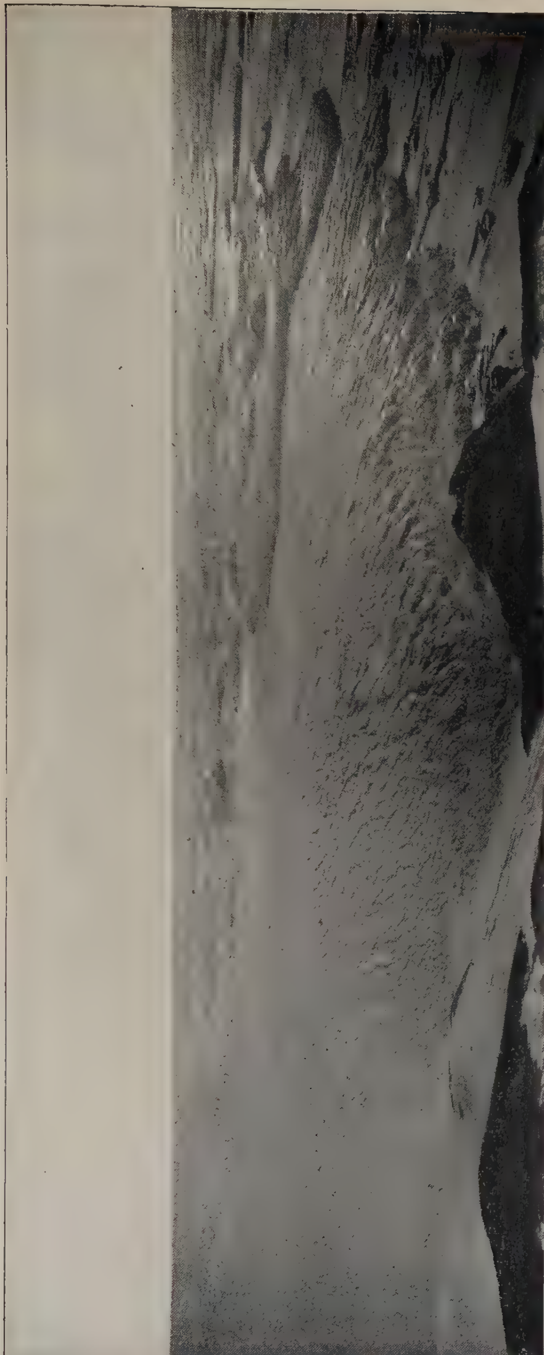
all lay upon land, for one could see dark fissures in its surface arranged in different systems. Everywhere this inland-ice ended at the sea in a steep edge 40 to 50 metres in height. The surfaces behind it might rise to 300 metres, but soon graded over into flat slopes so that one could not see the end." [5] (See Fig. 128 and plate 32.)

Of all the Antarctic inland-ice areas studied,[6] this seems to be the only one which furnishes a parallel to the continental glaciers which in Pleistocene times existed in North America and in Northern Europe. In all other cases a rampart of mountains encloses and materially modifies the physiography of the ice surface. It is, therefore, much to be regretted that we have no profile across its surface.

The crests upon the horizon of the inland-ice of Kaiser Wilhelm Land appeared not straight, but gently undulating. It was, therefore, concluded that the land beneath possesses a similarly undulating character. Near the ice margin, which was a cliff 130 to 165 feet high, soundings made through the neighboring sea-ice gave depths ranging from 550 to 810 feet, the greater depths lying to the westward. If only four-fifths of the ice is below sea level, the inland-ice of Kaiser Wilhelm Land must be aground nearly, if not quite to its edge. This is proven by the existence of a tide crack, which runs along the front and upon which the sea-ice moves up and down.

Fig. 128. — The inland-ice of Kaiser Wilhelm Land (after von Drygalski).

The convexly curving surfaces of the marginal zone of the



View of the inland-ice of Kaiser Wilhelm Land from the top of the Gaussberg (after v. Drygalski).

inland-ice are thus in sufficiently striking contrast with the horizontal top so characteristic of shelf-ice; but a no less noteworthy difference is found in the colors. Even from a great distance, the beautiful blue color of the inland-ice is noticeable, whereas the shelf-ice of the Ross Barrier is dazzling white. The blue color of the inland-ice shows that its surface is in general free from snow, and this appears to be characteristic of it during both winter and summer. Under the strong easterly winds which prevail, the snow falling upon its surface is able to find a lodgment only within the fissures and in the lee of the Gaussberg.

That the inland-ice is moving forward is sufficiently clear from the existence of great gaping fissures observed from considerable distances. These are particularly prominent in the step-like terraces of the near-margin portions, and the ice shows bucklings in the rear of them. Crevasses very generally appear upon the surface in parallel series, and sometimes two such series intersect each other at right angles (see Fig. 129).

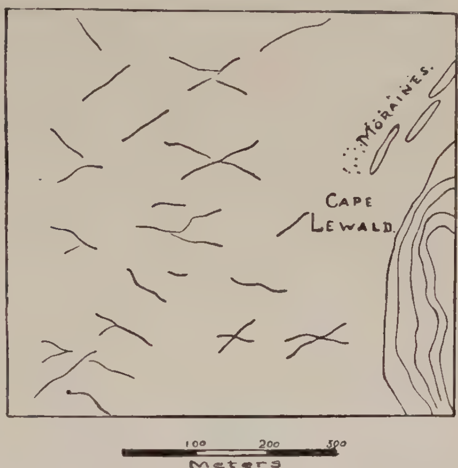



Fig. 129. — Intersecting series of fissures in the surface of the inland-ice to the west of the Gaussberg (after von Drygalski).

Such fissures were sometimes seen as they opened to the accompaniment of rumbling reverberations,[7] and, in general, their directions seemed to correspond to local disturbances above buried projections of the floor, or else to the strains set up due to general movement. The effect of the obstruction

of the Gaussberg in the path of the moving ice, was visible in local fissures developed within its neighborhood.[8]

Measurements of the rate of movement within the ice were made during a period of five months, and showed that at its margin the inland-ice moved forward at the remarkably uniform rate of about a foot per day. At a distance of two kilometres back from its margin, this rate had fallen off by $1\frac{1}{2}$ inches.[9] In spite of this, the aspect of the ice front was, in general, one of rest. No evidence of push was observed along its base.[10] In the vicinity of the only exposed land, the Gaussberg, the ice surface is lowered within a broad encircling zone due to the greater ablation in consequence of heat radiation from the rock surfaces (see plate 33 A). Here the stratification within the ice is made apparent by lines upon the surface, though elsewhere the only traces of banding are to be observed in fissures. On the surface of the bands were found the indications of "cryaconite" wells and water basins, no doubt from dust blown from the slopes of the Gaussberg.

It has been stated that the strong easterly winds suffice to keep the surface of the inland-ice swept of snow, with the exception of specially protected places such as the lee of the Gaussberg. Thus though the snow fall is heavy, the evidence showed that instead of increasing its thickness, the inland-ice surface is being constantly lowered, and thus confirms from a new region the many indications that the present is included in a receding hemicycle of glaciation. During five winter months the ice surface was found to have lowered through ablation by about 4 centimeters ($1\frac{3}{5}$ inches).

**The Blue Icebergs of Antarctica.** — In front of the inland-ice of Kaiser Wilhelm Land prodigious fragments of the continental glacier were found ranged in series more or less parallel and separated only by narrow lanes (*Gassen*). Farther out from the margin the bergs became less numerous

and eventually they were more scattered and more or less promiscuously frozen into the surface of the sea-ice.

From the typical tabular bergs of the Antarctic seas, these differ strikingly in their beautiful blue color as well as in their rounded contours. In Posadowsky Bay where they are frozen into the sea-ice, they could be studied to advantage. Their surfaces were found to be intersected by broad furrows which were steep on one side only, and smoothly polished upon the other.[11] The rounding of the angles is a result of filing off the surface by hard snow, driven by the storm winds.[12]

These blue bergs reveal, especially at their bases, bands of rock débris which must be regarded as portions of the ground moraine which have been raised upon a subglacial obstruction,[13] as has been shown to be characteristic of the margins of the Greenland continental glacier. The rock débris is here generally found in layers more or less parallel to the blue ice strata. The individual rock fragments are sometimes angular with a single scratched "sole" cut upon the surface. In other specimens there are several facets, or the block may be entirely covered with such smoothed and striated surfaces.

Professor von Drygalski, in his classification of Antarctic icebergs, has expressed his belief that the blue bergs arise from the common tabular bergs through the action of the wind driven snow, aided by evaporation.[14] The tabular bergs he believes, further, are derived from the margin of the inland-ice. This relationship to the usual tabular bergs it is especially difficult to accept, since the blue bergs are found mainly in contact with the inland-ice and near the shore, and are further characterized by the same colors and structures, whereas the usual tabular bergs seem to have more the properties of shelf-ice, though a portion only have the absolute uniformity of texture found in the best known example of shelf-ice, the Ross Barrier (see ante, p. 239).

**Origin of the West-ice.** — The peculiar labyrinthine surface of the West-ice, and its resemblance in places to a jam of blue bergs, as has been pointed out by Drygalski, in the writer's opinion, permits of an explanation of this mass of shelf-ice which is quite in harmony with the views of the British and Swedish explorers concerning the origin of shelf-ice in general. As von Drygalski has stated, the inland-ice surface of Kaiser Wilhelm Land, is swept clear of snow by the easterly storm winds, the sweepings finding lodgment only in fissures and protected places. A crowded fleet of blue icebergs massed upon the western or lee shore of Posadowsky Bay would have furnished the narrow lanes within which the snow could find lodgment. Still further to the west, the intervening spaces would have been levelled up with the tops, and thus a relatively even surface would result.

If cumulative loading of sea-ice by snow is to be assigned as at least one cause of the formation of shelf-ice, as seems now quite generally believed, it is evident that this process cannot go on where sea-ice is annually broken up and carried northward with the ice pack. *The essential condition for its formation is, therefore, an area within which the sea-ice either attains a greater thickness, or is so protected by the shores, that snow accumulates upon it from year to year.* Now it is worthy of note that the three great areas where shelf-ice has thus far been studied have all this character in common. The Ross Barrier is firmly wedged in Ross Sea between Victoria and Edward VII Land. The "terrace" of West Antarctica is held by the southeasterly storms against the west shore of a great gulf, and has crowded against the hook-like peninsula of West Antarctica. The West-ice of Kaiser Wilhelm Land is similarly developed upon the western or lee side of Posadowsky Bay, and its growth has been apparently facilitated by the assembling of a fleet of icebergs to collect the snow swept from the vast surface of the inland-

ice to the south and east. The British expeditions to Victoria Land have shown that vast quantities of snow blow off the barrier into the sea, and the collection of snow upon the northern side of the Nordenskiöld shelf-ice tongue is most illuminating in this connection (see ante, p. 234).

But additional evidence of this essential condition for the formation of shelf-ice, has been furnished by the recent French explorations. Gourdon has shown that near West Antarctica the normal winter's thickness of field ice is only about 16 inches, whereas in the sheltered upper end of Flanders Bay it had reached a thickness of between four and five metres (13 to 16 feet). Soft snow here lay upon the surface, with stratified névé below and compact ice at the bottom. At the margin of this terrace, which rose to a height of about a metre above the sea, immense rafts resembling in form, tabular icebergs were from time to time (in February) detached on long rectilinear cracks intersecting the terrace.[15]

In connection with the latest French expedition to the Antarctic, the great newly discovered bight which has been named Marguerite Bay, and which is sheltered behind Alexander Island, was found to have a similarly heavy cover of field ice reaching a thickness in this instance, of from 2 to 3 metres. The separation of ice blocks or overgrown floes from the margin, took place with fragmentation and apparently quite resembled the calving of tabular icebergs. Thus from the meagre reports of these late expeditions which have been published, it would appear that the intermediate stages in the transformation of field ice to shelf ice by accretion of surface snow are fast being supplied.[16]

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[1] The small ice-cap on Louis Philippi Land in Northern West Antarctica was in 1902 and 1903 crossed by Andersson and Duse from Hope Bay to Erebus and Terror Gulf, a distance of about 22 miles (Norden-

skiöld and Andersson, "Antarctica," 1905). The "upper terrace" which was just reached by Nordenskiöld near King Oscar Land probably represents inland ice.

[2] Brown, et al., "The voyage of the 'Scotia,' etc.," 1906, p. 236.

[3] E. Philippi, l.c., p. 11.

[4] E. von Drygalski, "Zum Kontinent des eisigen Südens, Deutsche Südpolarexpedition, Fahrten und Forschungen des 'Gauss,' 1901–1903," Berlin, 1904, pp. 668, 21 pls. and maps and 400 cuts. E. Philippi, "Ueber die Landeis-Beobachtungen der letzen fünf. Südpolar-Expeditionen," *Zeit. f. Gletscherk.*, vol. **2**, 1907, pp. 6–8.

[5] E. von Drygalski, l.c., p. 241.

[6] The "upper terrace" off King Oscar Land may prove to be another instance.

[7] Cf. Peary, ante p. 129.

[8] E. von Drygalski, "Deutsche Südpolar-Expedition, 1901–1903," vol. **2**, heft I, legends of plates.

[9] E. von Drygalski, "Die Bewegung des Antarktischen Inlandeises," *Zeit. f. Gletscherk.*, vol. **1**, 1906–1907, pp. 61–65.

[10] E. von Drygalski, "Zum Kontinent, etc.," p. 305.

[11] This, it will be remembered, was a characteristic structure upon the surface of the west-ice.

[12] E. von Drygalski, "Zum Kontinent, etc.," p. 305. Also Philippi, l.c., p. 10.

[13] Philippi, l.c., p. 11.

[14] E. v. Drygalski, *Sitzungsber. bay. Akad. Wiss.*, Math.-Phys. Kl., 1910, pp. 10–13 (reprint).

[15] Gourdon, *Exp. Ant. Franc.*, 1903–1905, 1908, p. 125.

[16] Charcot, "Rapports préliminaires, etc.," 1910, p. 51.

# CHAPTER XV

## THE ANTARCTIC CONTINENTAL GLACIER WHERE BEHIND A MOUNTAIN RAMPART

**Inland-ice in Victoria Land.** — The inland-ice of Victoria Land unlike that in Kaiser Wilhelm Land is held within an encircling rampart of high mountains — the Admiralty, Prince Albert, Queen Alexandra, and smaller ranges joined one to the other in a long chain. Its physiography is, therefore, in important respects different from that just described. Held back by the ranges, as by a gigantic retaining wall, the inland-ice now finds an outlet through somewhat widely separated and relatively narrow portals. These gateways have already been referred to as outlets, and to the southward they are, so far as known, the Skelton, Mulock, Barne, and Shackleton Inlets and the Beardmore Glacier (see Fig. 134, p. 258); while farther to the north, are the Reeves,


Fig. 130. — Section across the margin of the inland-ice of Victoria Land in a direction westward from McMurdo Sound (from data of the Scott expedition).

David, and Ferrar Glaciers. Some of the latter are, however, apparently no longer in service as outlets for the ice.

**Marginal Cross Sections of the Inland-ice along the Outlets.** — Thanks to the plucky efforts of British explorers, we

are fortunate in having no less than three sections across the margins of the inland-ice. These are on the lines of the Beardmore and Ferrar Glaciers, and between the David and Reeves Glaciers — the Backstairs Passage. The earliest of these was made by Scott on an east and west line westward from McMurdo Sound and up the Ferrar outlet. Later, Shackleton made his section more nearly upon a north and south line up the Beardmore outlet and toward the South

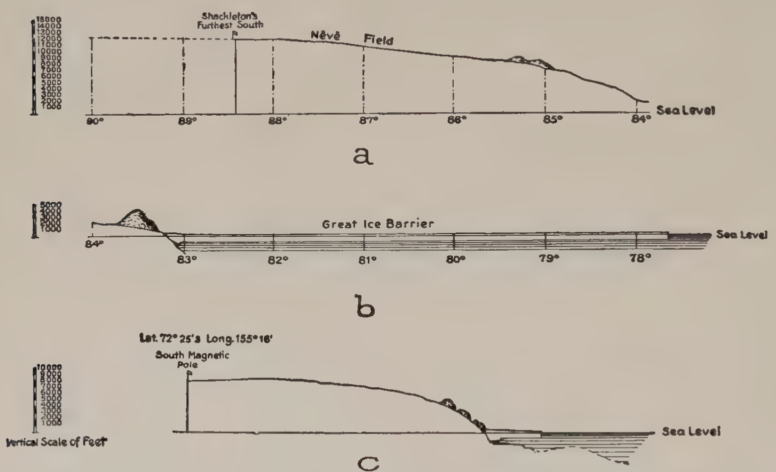


FIG. 131 (*a* and *b*). — Section across the Great Ross Barrier and up the Beardmore outlet to and upon the ice plateau of Central Antarctica (after Shackleton, but with barrier portion added). The part *b* should be joined to the right of *a*.

(*c*) Section across the Drygalski ice barrier tongue and up the Backstairs Passage on to the inland-ice in a direction toward the south magnetic pole (after David).

Pole; while David of the Shackleton party travelled in a direction nearly northwest from a point in latitude 75° S. up toward the south magnetic pole upon the plateau (see Fig. 130 and Fig. 131, a, b, and c).[1]

While not large when compared to the Ross Barrier to which it contributes its ice, the great Beardmore outlet compared with other streams of ice is by far the greatest known. On the map of Fig. 134, p. 258, we have added the Great

Aletsch Glacier of Switzerland drawn to the same scale in order to bring out this contrast. The area of the Beardmore outlet is in excess of 5000 square miles, its width is in places about 50 miles, and its fall about 6000 feet with an average of 60 feet to the mile throughout its entire length. Its surface showed every variety from soft snow to cracked blue ice. Crevasses were everywhere, some of them descending to hundreds and perhaps even a thousand feet. An ancient medial moraine was largely buried beneath its surface.

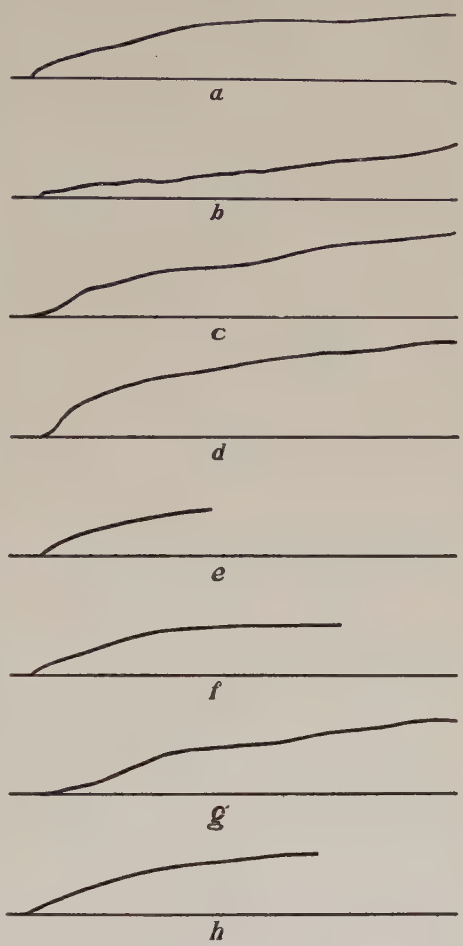


Fig. 132. — Comparison of sections across the margins of the continental glaciers of Greenland and Antarctica. (*a*) West Greenland (Peary); (*b*) West Greenland (Nordenskiöld); (*c*) Southwest Greenland (Nansen); (*d*) Southeast Greenland (Nansen); (*e*) South Greenland (Garde); (*f*) Victoria Land west of McMurdo Sound (Scott); (*g*) South Victoria Land (Shackelton); (*h*) North Victoria Land, Antarctica (David).

All the sections up the outlets show in common a steep slope near the margin and gentler grades above; as was found to be characteristic also of the margins of the Greenland continental glacier — an ice body

similarly held in by a wall of mountains (see Fig. 132). The Antarctic sections are like them also in the step-like alternation of steeper and more gradual slopes in the vicinity of the margins, the steeper slopes being deeply crevassed in a transverse direction.

Once the plateau surface has finally been reached, all sections are alike in the monotony of the surface, no irregularities in excess of a hundred feet being encountered. All irregularities of surface are here due to sastrugi deposited and later cut out by the fierce blizzards from the surface of the plateau. The plateau is, however, in no case reached when the mountain rampart has been passed, though the surface slopes continue to become more gradual. Within its retaining mountain wall the surface of the inland-ice is, therefore, flatly domed or shieldlike. It is the same in general form, though on a vastly grander scale, as the domed ice islands encountered off the coast (Fig. 110 and pl. 29 A). Above the great Beardmore outlet the surface continues to rise in terraces with crevasses upon the steeper slope, and these very properly led Shackleton to the belief that the ice here rests in moderate thickness upon a steeply sloping floor. The

Fig. 133. — View from above the Ferrar outlet looking from the inland-ice toward the outlet and showing the dip of the surface produced by the indraught of the ice (after Scott).

ridges rise abruptly with a great crevasse at the top of each and a descent upon the other side of perhaps fifty feet on a grade of one in three. Then smaller ridges and new waves of pressure ice are encountered, the undulations of the first

order of magnitude being separated by an interval of about seven miles.

**Dimples upon the Ice Surface above the Outlets.** — In Greenland it was found that the tongues of ice which push out through gaps in the mountain wall, the outlets, show above them a dimple in the surface caused by the indraught of the ice from the near-lying portions of the plateau.[2] The same characters pertain to the ice of Victoria Land.[3] A photograph by Scott looking back on the line of his route toward the outlet up which he had come, shows this very clearly. In Fig. 133, drawn from his view, we have added a dashed line to bring out the dip in the ice surface. Farther down the outlet this concavity of the ice surface obtains,[4] but in the lower reaches it changes to a convexly moulded form. Upon the Beardmore outlet this concavity of the surface with tendency to form an amphitheatre above is brought out upon Shackleton's map (see fig. 134).

Above the Ferrar Outlet Scott found the transition from the névé surface of the plateau to the outlet ice not a gradual one, but abrupt, the outlet having a corrugated surface of massive blue ice. The surface of the plateau ice is everywhere carved by the wind drift to form sastrugi of erosion which will be discussed in connection with the winds of the plateau.

**Ice Aprons below Outlets.** — At the foot of each active outlet, the ice is discharged upon the shelf-ice in an *ice apron* which spreads out laterally as well as in front (see fig. 134). In front of the Beardmore outlet this apron rises to a height near its medial line of between 400 and 500 feet above the general level of the barrier surface.

**Moats about Rock Masses.** — About the continental glacier of Greenland wherever the rock projects through its surface, local melting results from heat radiation from the rock surface (see p. 169). Except when filled in with drifted snow

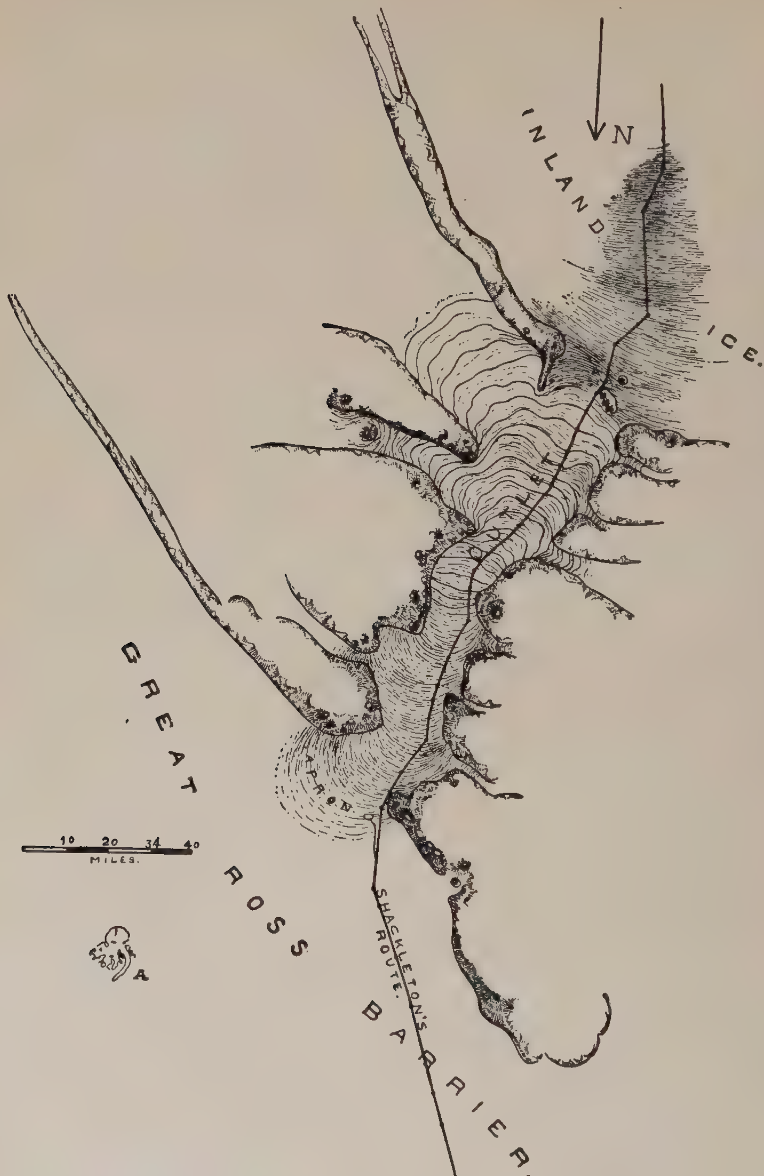


FIG. 134. — Map of the Beardmore Outlet from the inland-ice of Antarctica to the Ross Barrier. Note the dimple at head and ice apron at foot (after Shackleton). In the same scale the Great Aletsch glacier (*A*) is added.

*A.* The Gaussberg of Kaiser Wilhelm Land with ice surface depressed about it (after v. Drygalski).

*B.* Moat surrounding projecting rock mass. Inland-ice of Victoria Land (after Scott).

or when ice pressure has closed this gap, a deep and narrow depression surrounds the rock mass. This has been designated a *moat* from its resemblance to the moat surrounding a castle.[5] The same holds true of Victoria Land, where the wall of mountain ranges offers essentially the same conditions (see Plate 33 B).

**Mountain Glaciers on Outer Slope of the Retaining Ranges.** — Many of the well-known types of mountain glaciers [6] are found in numbers on the outer slope of the mountain wall which hems in the continental glacier of Victoria Land. The scale of these is large, like everything in the region, but the internal movement in most cases is slight, and the larger number are in a relatively stagnant condition. The Blue Glacier, which starts in the Royal Society Range, is cited by Ferrar as an example of the Norwegian ice cap type,[7] and ends at tide water in a cliff between 70 and 80 feet high on McMurdo Sound. Glaciers of the Alpine type occur according to the same authority in great profusion in the Royal Society Range. With them are associated horse-shoe or corrie glaciers, and these are especially well represented at the foot of the Inland Forts. The presence of the cirques here as everywhere calls attention to the peculiar eroding process which distinguishes mountain glaciers from their mightier neighbors of the continental type.

There is but little superglacial material upon the surface of the mountain glaciers, the lateral and medial moraines of the Ferrar glacier being merely long lines of large stones with very little finer material. About the margins, however, moraines are found near the bottom intercalated with blue ice, and at one point englacial rock débris was seen pushed up to form a surface moraine where two glaciers meet coming from opposite directions.

**Ice Slabs.** — Glaciers of an essentially new type, which Ferrar has referred to as *ice slabs,* are in the cases which he

cites masses of ice about 50 feet in thickness and from 4 to 6 square miles in area. These appear to be the dead aprons of true piedmont glaciers, from which the feeders have disappeared. They offer the most striking illustration of the necessity for some modification of our views concerning the nourishment and ablation of glaciers in polar latitudes, where, as we shall see, wind may be a far more important factor than temperature, and where melting occurs only under special conditions. These ice slabs seem clearly to be the relics of piedmonts retained during a receding hemicycle of glaciation. Were the changes in their form and size due to a general rise of the air temperature only, since the slabs are in the lower levels, they should first disappear; but where there is practically no melting at all save in the vicinity of exposed rock surfaces, or in connection with strong local foehn winds, the relatively narrow and tributary ice streams, surrounded as they are on all sides by rock, would probably be the first to disappear. The mountain valleys, moreover, are the natural channels of the hot and dry foehn winds.[8] If formed below true outlets from the inland ice, the recession of the parent ice mass would alone suffice to explain them, since this might cut off their nourishment.

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[2] Hobbs, *Proc. Am. Phil. Soc.*, vol. **49**, 1910, pp. 87–90.

[3] Scott, l.c., vol. **2**, pl. opp. p. 240, lower view.

[4] Scott, l.c., pl. opp. p. 224, upper view.

[5] *Proc. Am. Phil. Soc.*, vol. **49**, p. 117.

[6] *Geogr. Jour.*, vol. **35**, 1910, pp. 147–148.

[7] Ferrar, l.c., pp. 462–463.

[8] David, l.c., p. 151.

## CHAPTER XVI

### CLIMATIC CONDITIONS WHICH AFFECT THE NOURISHMENT OF ANTARCTIC ICE MASSES

**The Greenland Ice in its Relation to the Antarctic Continental Glacier.**—The conditions of climate which determine the alimentation of ice masses within polar regions are not identical with those which have been worked out from study of the local mountain glaciers which now exist in low latitudes. This has already been pointed out for the great continental glacier of Greenland.[1] It was found that the vast surface of the ice dome of Greenland controls the air circulation above it; and we see that in proportion to their dimensions great continental glaciers must exert larger and larger effects, and even, it may be, eventually put a limit upon their own extension.

The continent of Greenland is not located in proximity to the pole, and hence we are able the better to assert that the conditions which we there find are not explained by the planetary system of the winds. This is fortunate for our study of the Antarctic region, since there an elevated plateau is more nearly centred above the earth's axis, and more or less unknown and mysterious causes might otherwise be invoked to explain a system of circulation and a climatic condition which in most respects are identical with those worked out with some care for the northern continental glacier. For

these reasons the northern ice masses should be studied first, because of the light which they throw upon the problems of Antarctic glaciation.

**Air Temperatures, Humidity, and Insolation.** — The Antarctic, as already pointed out in an earlier section, is in contrast to Arctic regions, characterized by greater severity of climate, by lower average annual temperatures, and by less temperature range between winter and summer (ante, p. 188). Over the Greenland ice the relative humidity of the air is extremely high, while its absolute humidity, because of low temperature, is very low. Even on the margins of the Antarctic continent this was early proved to hold true. On between thirty and forty per cent of the days that he was south of the parallel of 60° S., Ross found the air completely saturated with moisture. Racovitza reports from the "Belgica" expedition that the air was almost constantly saturated with water vapor.[2]

Insolation, or solar radiation, on the borders of Antarctica is during the summer months considerable. On the "Belgica" expedition at the end of December, Racovitza found that a black-bulb thermometer when exposed in the sun registered 113.2° F., when the air temperature was only 31.6° F., although this effect was hardly felt upon the ice pack.[3] Bernacchi with a black-bulb thermometer frequently obtained at Cape Adare temperatures above 80° F., while temperatures in the shade were below the freezing point.[4]

**Nature of the Snow Precipitated in Antarctica.** — Rain is unknown on the Antarctic continent and most of the snow is precipitated in spring and summer[5] and at relatively low temperatures. Observations made in Victoria Land have shown that if precipitated near the freezing point, the snow is of one or the other of two types. With a sudden fall of temperature the *sago* or *tapioca* snow was precipitated in the form of felted spheres one-tenth of an inch or more in diameter. Otherwise large six-rayed feathery flakes similar to those formed in

warmer climates resulted. In colder temperatures the air became filled with minute ice crystals which were only one one-hundredth of an inch in diameter and descended from a cloudless sky.[6] This form of snow thus resembles the "frost snow" described by Nansen as characteristic of the ice plateau of Greenland.

When the softer snow falls in summer time, if the weather becomes colder, the snow compacts itself and becomes hard. Such superficial hardening yields a "pie-crust" surface and the snow below is soon firmly bound together so as to yield the usual "smooth-sledging type of winter snow-ice."

Upon the plateau a surface of somewhat different character is produced when solar radiation on quiet summer days has melted a thin superficial layer of the snow. Under such conditions large and beautiful reconstructed ice crystals develop which are about one-half inch across and one-sixteenth of an inch in thickness. These develop throughout a layer extending about one-half an inch below the surface. Covered with these sheets of brightly reflecting ice crystals, the snow surface glitters "like a sea of diamonds."[7] The heavy sledge runners rustle as they crush the crystals by the thousand. With the first strong wind these crystals are picked up and drifted away, the sastrugi in consequence exhibiting such scaly crystals on their lee sides, whereas the windward surfaces are much eroded and furrowed by the wind.[8]

Off Kaiser Wilhelm Land it was noticed that late in August when the actinometer had risen for the first time above freezing, traces of fusion began to appear upon the snow surface. These consisted in a smoothening and hardening of the surface, and in the development of sublimed crystals beneath the crust. This last feature was, moreover, not found in those crusts which were formed by wind pressure and were observed alike upon the north and south sides of drifts.[9] The amount of the annual snow fall above the Great Barrier has

already been discussed (see ante, p. 223). Upon the plateau snow is carried in the air and was observed to within 110 miles of the pole. It is significant that the snow comes mainly in the summer time and invariably from the south or southwest in connection with the peculiar blizzards. On several occasions it was observed that whereas in the earlier part of the blizzard the snow was largely redistributed snow in the form of drift, a new fallen snow appeared near the end accompanied by a rise of temperature (see below, p. 269).[10]

**Winds upon the Continental Margins.** — Throughout the margins of the Antarctic regions the general direction of strong surface winds seems to be within the quadrant between south and east. In this Wilkes, Ross, Wyville Thomson, and other navigators of the far southern seas are in agreement. The zone of prevailing westerlies travelling southward with the sun may, however, at points near the Antarctic Circle sometimes bring about a partial seasonal reversal of this wind direction. Thus Arctowski reported high air pressure at the solstices and low pressure at the equinoxes to the westward of West Antarctica, with easterly winds predominating over westerly, but with a relative high frequency of the latter in the winter months.[11]

At Cape Adare in Victoria Land the prevailing winds were found by Bernacchi to be from the east-southeast and southeast in a very marked degree. Measured in observation hours the calms were, however, even more important, there being 1033 hours of calms, 973 hours of winds from the southeasterly quadrant, and only 275 hours of winds from all westerly points whatsoever.[12]

At Cape Royds on McMurdo Sound, where Scott's expedition wintered, the winds were much modified by local conditions, but were generally from the east or southeast. No winds, but only light airs, came from the west or northwest. Blizzards invariably came from the south or southwest.[13]

The Shackleton party in almost the same locality reports either gentle northerly winds whose velocity seldom exceeded twelve miles an hour, or winds from the south-southeast or southwest, the latter ranging from gentle breezes to fierce blizzards. A northwesterly wind was rare.[14]

In Kaiser Wilhelm Land an absolute rule of easterly winds was observed, and gales from the southeast kept the surface of the inland-ice swept clear of snow.[15]

**The Antarctic Continental (Glacial) Anticyclone.** — The prevalence of southeasterly winds about the borders of the Antarctic continent finds its only explanation in the existence of an area of high atmospheric pressure above the continent. Sir James Ross, as long ago as 1840, obtained increasingly high atmospheric pressures in his cruise southward in the Ross Sea. A South Polar anticyclone was as early as 1893 declared to exist by Sir John Murray in a paper read before the Royal Geographical Society and printed in the Geographical Journal.[16] Unfortunately the theory of polar eddies promulgated by Ferrel[17] and adopted by Davis in his in many respects excellent treatise[18] is responsible for a general prevalence of incorrect views concerning the winds of both the earth's polar regions. As pointed out by Buchan in 1898, the low pressures required by this theory do not exist, and in place of the supposed northwesterly winds blowing homeward toward the poles, as required by the theory, we find in the Antarctic southeasterly and easterly ones.[19] If Ferrel's theory were correct, Antarctica would be a land of rain and fog instead of what it is known to be.

Bernacchi in 1901, as a result of his very important meteorological studies in connection with the "Belgica" expedition, set forth the evidence for the Antarctic anticyclone in a most convincing manner. Speaking of the prevailing southeasterly winds of the region, he says: —

> Their frequency and force, the persistency with which they blow from the same direction, the invariable high rise in the temperature, their dryness, the motion of the upper clouds from the N.W., and, finally, the gradual rise in the mean height of the barometer to the south of about latitude 73° S., seem to indicate that the Antarctic lands are covered by what may be regarded practically as a great permanent anticyclone, with a higher pressure than prevails over the open ocean to the northward.[20]

The complete verification of the existence of an Antarctic anticyclone has, however, been furnished by Shackleton, who in his journey across the ice plateau to within one hundred and ten miles of the earth's southern pole has brought back the knowledge that throughout the entire distance the winds blew strongly nearly all the time from the south or southeast with an occasional change to the southwest, and that all sastrugi pointed to the southward.[21]

**Wind Direction determined by Snow-ice Slope.** — It is the author's belief that over the Antarctic continent this anticyclonic circulation of the air is not determined in any sense by latitudes, but is a consequence of air refrigeration through contact with the elevated snow-ice dome, thus causing air to slide off in all directions along the steepest gradients. For the continent of Greenland this has now been fully demonstrated through the work of several observers, but especially of Commander Peary;[22] and there is every reason to think that the conditions in Antarctica are essentially the same. Upon this supposition the prevalent winds and the strongly marked sastrugi which were observed by Scott, Shackleton, and David upon the ice plateau, find a simple explanation. The strikingly local character of the winds about the margins of the great Ross Barrier are on this assumption likewise accounted for.

As already stated, Shackleton encountered on his journey of about two hundred miles across the ice plateau strong

winds blowing only from the southerly quarter, and the sastrugi showed this direction only. Scott on his plateau journey westward for about two hundred miles from McMurdo Sound, in a latitude eight to ten degrees lower, likewise encountered winds of constant direction here from the west-southwest, and a single set of sastrugi with directions varying only between west by south and southwest by west. Eight to ten degrees farther north, and upon what now appears to be a relatively narrow peninsula of the con-


FIG. 135. — Sketch map showing directions of the sastrugi along the line of David's course to the south magnetic pole. The direction of the arrows indicates the direction of the wind as evidenced by the sastrugi (based on Shackleton's map and David's narrative).

tinent, David for the first time found variable wind directions and several sets of sastrugi. A more careful examina-

tion of his data confirms the view that the air currents upon the peninsula are determined wholly by the direction of snow slope upon the plateau, as is apparent from Fig. 135. Off the coast the sastrugi betrayed the evidence of the strong southerly blizzards and also of winds which blew down from the plateau through the portals of the outlets. Until the highest point of the plateau had been reached, winds and sastrugi alike indicated a sliding down on the slopes toward the coast. On January 11th, when there was "no appreciable general up-grade now," it was noticed that the sastrugi "had now changed direction, and instead of trending from nearly west or north of west, eastwards, now came more from the southeast directed towards the northwest." To the west of the summit as shown by the map, the sastrugi point southeastward, indicating that the shore line doubtless continues its direction to the westward from Cape North. Returning from the South magnetic pole toward the crest of the dome, David states, "We had seen from the evidence of the large sastrugi that blizzards of great violence must occasionally blow in these quarters, and from the direction of the sastrugi during our last few days' march, it was clear that the dominant direction of the blizzard would be exactly in our teeth." [23]

**The Foehn Blizzard of the Ice Plateau.** — Next to the observation that the prevailing winds blow outward from the interior of the continent, the nature of the winds themselves is most characteristic of an anticyclone developed above an ice plateau as we have become familiar with it in Greenland. In Victoria Land these winds sometimes blow with a violence of seventy to eighty-five or more miles per hour, and are probably the most violent that are anywhere known. The summer blizzard lasting for three days, which Shackleton encountered near his farthest south and at an elevation in excess of 10,000 feet may be cited as an example.[24]

Despite the fact that these blizzards in summer at least appear to bring snow, the wind may be described as dry. Though at first cold, and, in fact, having its origin, it would appear, in a general lowering of the temperature during a period of calm, in a later stage the temperature rapidly rises, due to the foehn effect. In Victoria Land an increase of as much as 45° F. has been observed to take place within twenty-four hours.

The sequence of events during a blizzard begins with gentle northerly winds which continue for a day or two, during which temperatures are low. David has suggested that during this time air is flowing south to take the place of air whose volume has been reduced as a result of the heat abstracted from it on the ice surface. Then there follow two or three days of absolute calm, during which the temperature continues to fall. Still further cooled upon the ice surface, the air, a week or more after the calm begins, starts to move outward in all directions and so develops (on the edge of the barrier) a southeasterly blizzard. Simultaneously with this movement the steam cap over the volcano of Erebus, which normally indicates an upper current from the northwest, swings round to the north and takes on an accelerated movement, as though it were being drawn from that direction to supply air to the void resulting from the violent surface current toward that direction. Corresponding to the increased velocity, the normal foehn effect near the pole must be much increased, as it is also on the descent of the surface current from the plateau. As soon as the warming of the polar air from this cause has become general, the high air pressure of the central area is automatically reduced, and thus the blizzard gradually brings about its own extinction. To the warming effect of the descending air current there is rather suddenly added the latent heat of condensation of the moisture when it is precipitated in the form of fine ice

crystals within the air layers just above the snow-ice surface. The rather sudden termination of the blizzard may be thus in part explained. David has suggested that a "hydraulic ram effect" may be induced in the air of the upper currents, since the steam clouds over Erebus, normally the antitrades, are temporarily reversed in direction at the termination of a blizzard, and for a short interval blow northward.[25]

Foehn winds were experienced by the German expedition off Kaiser Wilhelm Land, and von Drygalski has remarked upon the fact that the air above the inland-ice is more transparent than that over the neighboring sea-ice, this arising from its greater dryness due to its dropping down from the heights in the interior. Frozen sleeping bags exposed in the day-time on the slopes of the Gaussberg became soft and dry within a surprisingly brief time, and particularly during the storms. An ice wall built up about the tent was so sucked up by the dry wind as to present an indented and ragged surface.[26]

The local effect of the foehn is naturally accentuated within the steep and relatively narrow outlets from the interior plateau. When ascending to the plateau from the Drygalski tongue, David encountered a hot foehn which thawed the snow, and upon the glacier tongue below the effects of earlier foehns were found in the channelled surface and the buried water tunnels.[27]

At the winter station of the Swedish Antarctic Expedition on Snow Hill Island, West Antarctica, even in the most severe winter weather, sudden rises of temperature occurred which lasted for a few minutes only, but which carried the mercury in the thermometer up to $9\frac{1}{2}°$ C. (49° F.), a point higher than is reached even in the summer season. Such remarkably abrupt changes Nordenskiöld believes can only be explained by very sudden falls of air, which in consequence become heated adiabatically.[28]

The discovery of the origin of both the Greenlandic and Antarctic warm winds in a refrigeration of surface air layers by contact with snow-ice masses raises the question whether the so-called foehn winds of mountain regions have not a similar cause in contact refrigeration. It is thus of special interest to learn from studies of foehn winds where no such extended snow-ice surfaces are to be found, that this explanation has been offered, and that they are now believed to be due to refrigeration by contact with elevated mountain surfaces.

In the Bavarian highlands the foehn winds are found to be preceded by anticyclonic conditions and a very stable stratification of the atmosphere. The foehn sets in earliest at the high stations, and during its descent to lower levels reaches stations having the same altitude simultaneously, even though these be located in different valleys. Stagnant air cooled by contact with the mountain sides always starts the descending currents. The cold air drains away to lower levels, and sometimes brings about a reversal of normal conditions so that the higher air temperatures are at the higher levels. When the currents have become established, they flow down the valleys like rivers and the curve of increase of temperature is found to correspond to the dry adiabatic curve for air.[29]

Recent studies of the warm outflowing currents of the Rocky Mountain regions have shown that these flow eastward off the range as a broad sheet which has been followed for many hundreds of miles in a north and south direction.[30]

**Wind Transportation of Snow.** — For the Greenland continental glacier it has been shown that the strong winds are probably a far more potent factor in the transportation of the snow than are all the other influences combined. The same would appear to be no less true of the Antarctic continent.[31] During strong southerly gales the snow upon the

surface is picked up by the wind and the air is filled to a height dependent upon the wind velocity. This in the case of moderate winds may be only a foot or two, so that dogs would be submerged in it, though ponies would still have their heads clear. During fierce blizzards, however, the air is loaded with snow to a much greater height.[32]

The strong winds of the region, as we have seen, always blow down off the plateau in the direction of the steepest gradients. The southerly blizzards encountered by Shackleton near the end of his southern journey entirely swept away all surface snow of recent deposit, leaving for the return a hard and white snow surface resembling Carrara marble. Descending the Beardmore outlet, the surface for the first one hundred miles he likewise found swept clean, but the lower forty miles was buried deep under drift snow.[33] Above the Backstairs Passage David found the ice surface similarly hard and marble-like.

Over the Nordenskiöld shelf-ice tongue, snow is carried from the southern to the northern margin, where it builds a great ice-foot which the sea-ice pulls away in sections to form a high cliff. Within a zone surrounding the rocky islands off the coast of Antarctica, ice-foot or fringing glaciers are developed from the same cause. The Ross Barrier and other bodies of shelf-ice are built higher, and, as already explained, doubtless owe their origin to local snow deposit, probably in large part borne from long distances by the wind. The inland-ice of Kaiser Wilhelm Land is swept clear of snow by the southeast storms, and the snow removed is probably lodged farther to the west, where it forms the West-ice.

As upon the Greenland continental glacier, so here in Antarctica, the resemblance to Sahara conditions is most striking, the fine, hard snow grains driven by the wind behaving as does the sand of the desert. Says Gourdon:[34] —

Such snow has received the name *poudrin;* in accumulating upon the surface it has no consistency — the grains remain without cohesion. The foot has the sensation of sinking in fine sand. Certain marches reminded me of nothing so much as of those which at another time I had made in Southern Tunis.

Picked up by the wind this snowy powder is the *chasse neige,* veritable blinding clouds which at times acquire a formidable violence; one sees them rise in whirls above the crests, sweep the white plains and rob the glaciers of all the movable portions. A great part of this snow is borne to the sea; another part accumulates in long undulations called sastrugi; another, finally, protected behind some obstacle, ice or rock, is piled up in the form of dunes. In short, this snow behaves like the sand of the desert, and, further, like it, though of less intensity, it has eolian movements.

FIG. 136. — The lee side of a sand dune on the coast of northern California. Note the resemblance of the curve of profile to that of continental glaciers (after a photograph by Fairbanks).

Recognition of the importance of wind transportation in connection with continental glaciers raises the question as

to how far their peculiar marginal sections are controlled by this factor. There is evident in the sections across the margin of the inland-ice an approximation to a regular curve (see Fig. 132). The resemblance of this curve to the curve of profile on the lee side of sand dunes (see Fig. 136) is most striking. Fringing glaciers of both the Arctic and Antarctic regions are in reality dunes of granular sand like snow, and it seems likely that the margins of the inland-ice are broadly moulded by this process (see Fig. 137).

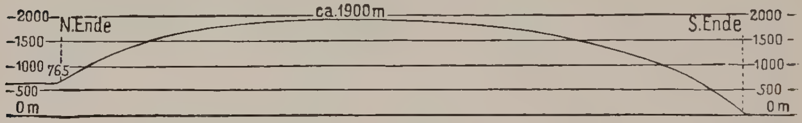


FIG. 137. — Section across the Vatnajökull of Iceland (after Spethmann and Thoroddsen).

The relative parts played by wind transportation upon the surface and by ice regelation and flow beneath it are yet to be determined. The sharp contact of névés now with blue glacier ice at the head of the Ferrar outlet appears to bear upon this point.

**High Level Cirrus Clouds the Source of Snow in the Interior of Antarctica.** — It has heretofore been thought open to question whether within the interior of Antarctica any snow is precipitated in the ordinary sense. The fact that the winds capable of transporting the snow all move outward upon the plateau and that to the farthest point reached by Shackleton what appeared to be new-fallen snow was encountered, almost makes it necessary to assume that even there snow reaches the surface of the plateau from the surrounding air and is not all of it merely lifted and again deposited by the wind. It is, however, clear that no moisture can there be derived from *surface* currents, since all move outward from the region. The only possible source of new snow is, there-

fore, the *high level* currents, which from cloud studies, as well as from the observations of Mt. Erebus, are clearly shown to supply the air of the Antarctic anticyclones.

As already stated, the dominant surface winds upon the continental margins come from the south and southeast, with the easterly component larger at the lower latitudes due to deflection by earth rotation. The upper currents come, in general, from the northwest quadrant and are more curved toward the south as they pass southward over the Ross Barrier.

Over the ice plateau the characteristic clouds which were observed are the high broken cirrus and cirro-stratus.[35] At times the peculiar " polar bands " or " Noah's Ark " clouds were seen stretching across the sky and converging at opposite points of the horizon, the direction of their movement being here always southerly.[36] *On the west of Ross Sea the direction of these polar bands was from the north-northeast or northeast curving round from the north. This is not in accordance with the theory of the polar anticyclone, but conforms to that of a continental (glacial) anticyclone, since the surface currents on the plateau in this vicinity come from the westerly quarter.*

In these high levels, clouds floating at an altitude certainly in excess of 14,000, and probably 25,000 feet, the moisture must be frozen, since the temperature of air ascending through 6000 feet only is adiabatically lowered by about 35° F. There is, however, the probability that in general this snow or ice is adiabatically melted and vaporized during its descent to the plateau, and subsequently congealed as it mixes with the cold air above the plateau surface. This would explain the clear skies which are so general over both Greenland and Antarctica during snows in the higher levels. It is of course true that the latent heat of fusion and vaporization of ice, abstracted as it is from the air during its descent within the eye of the anticyclone, will counteract to some extent the warming adiabatic effect; and it is

not improbable that the long duration of Antarctic blizzards and their somewhat sudden terminations accompanied by snowfall are explained in part by the transformations of latent and sensible heat.

Additional evidence for the continental and glacial rather than the polar nature of the Antarctic anticyclone is derived from the strong blizzards observed at the British winter quarters on McMurdo Sound. *Whereas the lighter gales came from the southeast and indicate a control by local conditions,*[37] *a blizzard of the first magnitude was not thus influenced, and always swept down from the southwest — that is, from the high plateau, and not from the pole, since otherwise the earth's rotation would have given it an easterly direction.* When its powers begin to wane, it is once more controlled by local conditions and the wind again comes from the southeasterly quarter.[38]

An apparent confirmation of this theory of the alimentation of inland-ice masses is to be found in Nordenskjöld's narrative of the sledge journey across Northeast Land (Spitzbergen) in 1873. While Nordenskjöld did not at that early day and on the basis of the single journey discover the important law of atmospheric circulation above an inland-ice mass, which the subsequent explorations, particularly of Peary, Scott, and Shackleton, have revealed, yet the presence there of essentially the same conditions is probable from his narrative.[39] The fine, hard snow was found to be almost constantly in motion along the surface, which was glazed and polished by its action. Under ordinary circumstances, this stream of rounded snow grains rose a few feet only into the air, but even then it was so troublesome as to be likened to the desert sand in the Sahara.

After the first day upon the inland-ice, during which the weather was clear, either snow-storms or dense snow mists were the rule, and several times a quite remarkable phenom-

enon was observed which we may best describe in Nordenskjöld's own words as rendered by Leslie:[40] —

> During our journey over the inland ice, we several times had a highly peculiar fall of —
>
> 1. Small, round snowflakes, sometimes resembling stars, of a woolly appearance.
>
> 2. Grains falling simultaneously, of about the same size as the snowflakes, but formed of a translucent, irregular ice kernel, surrounded by a layer of water, which, however, froze in a few moments after the fall of ice, and in a short time covered our sledge-sail, etc., with a thin and smooth crust, or fastened itself to our hair and clothes as small translucent ice-drops. During one such fall on the 5th June there were seen simultaneously a faint halo and a common rainbow, the temperature being 4° to 5° C. under the freezing point. [See Fig. 138.]

We have thus here to do with *irregular ice grains* enveloped in water, falling in sunlight near the glacier surface in a temperature 4 to 5 centigrade degrees below the freezing point, and in association with freshly precipitated felty *snow-flakes*. Since all the material of the glacier surface is snow, the source of the ice kernels must be within the upper atmospheric regions. We know of no source there save only the ice grains composing the cirrus clouds. The water envelope about the ice kernels would be explained by the adiabatic rise in temperature during the descent of these grains to the plateau within the eye of the anticyclone, and the sudden subsequent freezing would be explained by the arrest of the downward motion and the mixing with cold layers of air lying in contact with the glacier. The associated snow-flakes would be derived by


Fig. 138. — Section of one of the irregular ice grains enveloped in water which was precipitated together with snow-flakes upon the inland-ice of Northeast Land (after A. E. Nordenskiöld).

similar changes of temperature from those smaller ice grains which during their descent to the plateau had been entirely melted and vaporized, as well as from the vapor of the water envelopes about the ice kernels. It will be interesting to learn when the central areas of the Greenland and Antarctic glaciers have been similarly penetrated, whether a like phenomenon is characteristic of them.[41] The much higher altitudes and the lower temperatures make it, however, rather unlikely. While it thus appears to be true that the inland-ice of Northeast Land is able to induce a local glacial anticyclone within the atmospheric envelope, the somewhat smaller ice mass of the Vatnajökull in Iceland produces apparently no such disturbance.[42] This is probably not alone to be explained by the somewhat smaller dimensions of the Icelandic ice mass, but quite as much by the fact that it is near the centre of a fixed low pressure area of the atmosphere with disturbances of large extent and of exceptional violence. The problem of the size of ice carapace which under normal conditions is just able to induce a local anticyclone within the atmosphere is one of great interest, for with the initiation of this gas engine we reach an important turning point in the processes of glacier alimentation and depletion.

At the beginning of this volume it was stated that air temperature has come to be recognized as the chief factor in the initiation of glaciation. While this is true, the factor of temperature loses its dominance and becomes secondary in importance to wind currents so soon as the local anticyclone has been strongly developed. As we have seen, this anticyclone not only puts a stop to the nourishment of the glacier by moisture-laden air currents, but, in addition, it constantly transports the snow of the central portion to the margins. This process tends to reduce the altitude of the central portion of the mass as it extends the margins. With a continu-

ance of the process, the vigorous outward-blowing currents of the anticyclone extend the margins toward the sea, whereupon large amounts of snow are there deposited, dissipated, and consequently lost to the inland-ice. Were it not for the fact that the same engine pulls down the ice grains in the cirrus cloud masses so as to in part replace its earlier nourishment by the snow of low-level currents, the local anticyclone must quickly induce a receding hemicycle of glaciation, resulting eventually in its own extinction. It is, in fact, quite possible that a limit is set upon glacier size by the refrigerated air engine thus brought into existence, and that the great Antarctic glacier, now in a waning stage, is an illustration of this fact.

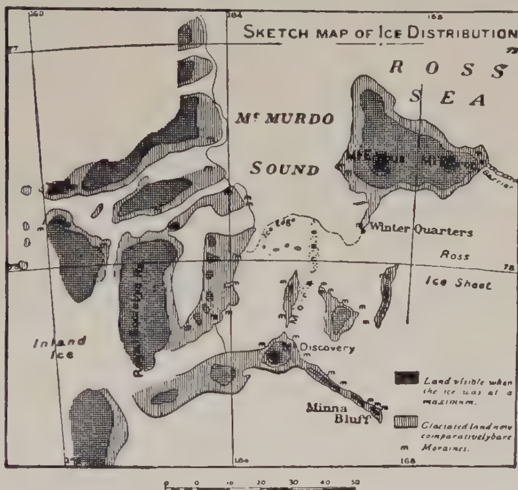


Fig. 139. — Sketch map showing the glaciated and the higher non-glaciated surfaces of the rock masses which protrude through the ice in the vicinity of McMurdo Sound (after Ferrar).

The warming of the air observed toward the close of an Antarctic blizzard, and the appearance at the same time of the soft and newly fallen snow in place of the lifted and driven snow of the earlier stages, both testify to the existence of the system of currents above described. Thus an adequate explanation is found for the disappearance of moisture congealed in the ice grains of cirrus clouds.

**Former Extent of Antarctic Glaciation.** — Studies of Greenlandic and Antarctic glaciation alike show that we live in a

receding hemicycle of glaciation. According to Scott the surface of the great inland-ice mass of Victoria Land was once from 400 to 500 feet above its present level.[43] The Ross Barrier has been at least 800 feet higher than now, since Dr. Wilson discovered moraines on the slopes of Mt. Terror at that altitude (see Fig. 139). The barrier must, therefore, have been aground, and in the view of Scott, it once filled all the Ross Sea as far out as Cape Adare. The Bellany Islands, much farther out and near the Antarctic Circle, are more heavily glaciated than is Victoria Land. Since 1840, when Ross sailed along its edge, the Ross Barrier has receded in places a distance of from twenty to thirty miles (see Fig. 113, p. 217). The Nordenskjöld shelf-ice tongue and the shelf-ice of Lady Newnes Bay are remnants of the older shelf-ice of Ross Sea and are now no longer adequately nourished. The mountain glaciers which now lie on the east slope of the mountain rampart of Victoria Land indicate clearly that they were once much more important than now. Most interesting of all are the ice slabs — dead piedmont aprons of which the feeders have disappeared.[44]

To-day it is highly probable that far more snow is blown from the borders of the continent out upon the sea-ice, and hence eventually melted in the water, than falls upon the continent and its shelf-ice margin. The recession is to-day in progress.

On the summit of the Gaussberg in Kaiser Wilhelm Land, and at a height of 350 metres (about 1140 feet) above the surface of the surrounding inland-ice, erratic blocks of gneiss were found, from which we conclude that this mountain was once entirely submerged beneath the inland-ice.[45]

In Belgica Strait (Gerlache Channel) of West Antarctica in the low latitude of 64° S. are evidences that this great trench, fully ten miles in width, was once completely filled by a great glacier tongue which pushed westward into the Pacific. The

lateral moraines of this ice mass, fifteen to twenty feet in height, are found to-day between sixty-five and eighty feet above the sea level, and the depth of the channel is in the neighborhood of 2000 feet.[46] *Roches montonnées* and erratic boulders found upon the islands of the Palmer archipelago to the west of Belgica Strait afford further confirmation of the once much greater extension of the ice. Other data from the same region have been furnished by J. G. Andersson,[47] Otto Nordenskjöld [48] and Gourdon.[49] The last-mentioned observer is, however, of the opinion that the present rate of recession as estimated from the retreat of the Ross Barrier since 1840 has been given too much weight. That the present is, however, a hemicycle of recession, all observers are agreed.

There is an interesting theoretical problem connected with a possible future extinction of the Greenland and Antarctic continental glaciers. For the latter, at least, the dimensions of the superimposed fixed anticyclone are such that the highest surface of the snow-ice dome may be regarded as in some sense an eccentric earth pole in the wind system comparable to one of the eccentric magnetic poles. The high-level air currents traveling as anti-trades are at this point drawn down to the surface from all sides and here begin their return journey equatorward as surface currents. Were the glacier removed entirely, certain changes in the wind system of this part of the globe would certainly be brought about. The glacial studies herein set forth show quite conclusively that it is the dome-like surface of the snow-ice mass with its universal outward grades always increasing in value toward the periphery, quite as much as its refrigerating property, that is responsible for the vigor of the glacial anticyclone.

We are still without knowledge concerning the elevations or the configuration of the underlying Antarctic basement,

though well convinced that it must constitute an upland of some sort. The studies of v. Ficker[50] in the Eastern Alps and of Bigelow and others in the American Cordillera, indicate that on bare mountain slopes there is at times a sliding off of refrigerated surface air under essentially anticyclonic conditions. It seems likely, therefore, that a continental anticyclone would persist over an outward sloping Antarctic continent after the total extinction of the ice mass, even though greatly reduced in vigor.

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[30] *Science*, N.S., vol. **32**, Oct. 7, 1910, p. 460.

[31] See among others: Royds, *Geogr. Jour.*, vol. **25**, 1905, p. 387; O. Nordenskiöld, *Zeit. f. Gletscherk.*, vol. **3**, 1909, p. 325.

[32] "The air is entirely filled with drifting snow, which strikes you like a sand-blast. You can not face it but have to stumble on to wherever you may be going with your head down and arms protecting your face, and even could you face it, you are not able to see a yard all around you." (Lieut. Royds, in *Geogr. Jour.*, vol. **25**, 1905, p. 389.)

"Nothing more appalling than these frightful winds, accompanied by tons of drift snow from the mountains above, can be imagined." (Bernacchi in Borchgrevink, l.c., p. 306.)

"During snow storms it was characteristic that the snow did not drive high. The masts of the 'Gauss' were frequently free, while the snow below was so thick that nothing could be seen." (E. von Drygalski, "Zum Kontinent, etc.," p. 372.)

"Nothing is more trying in the torment than this powder of murderous crystals which whip the face and eyes and prevent one from keeping his direction. Walking is, therefore, at times impossible and the traveller must bury himself in a hole in the snow until the blizzard is over." (E. Gourdon, in Charcot, *Expédition Antarctique Française*, 1903–1905, p. 74.)

[33] Shackleton, vol. **2**, p. 19.

[34] Gourdon, l.c., pp. 74–75.

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[36] David, Narrative, l.c., pp. 91, 168, 171, 175.

[37] The winter quarters were located in a gully or "gap" running down from the barrier surface toward the sound in a direction from southeast to northwest. (Royds, l.c., p. 387.) (See fig. 139.)

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[40] A. Leslie, l.c.

[41] Shackleton's journey has made clear that the boss of the ice plateau is far to the southwest of his route.

[42] Personal communication from Dr. Th. Thoroddsen.

[43] Scott, vol. **2**, p. 423.

[44] Scott, l.c., vol. **2**, pp. 422–425.

[45] E. von Drygalski, *Zeit. f. Gletscherk.*, l.c., p. 311. Also Philippi, l.c., p. 7.

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[48] O. Nordenskiöld, *Zeit. f. Gletscherk.*, vol. **3**, 1909, pp. 329–331.

[49] Gourdon, l.c. (1908), pp. 116–121.

[50] Von Ficker, l.c.

## AFTERWORD

**The Two Contrasted Glacier Types.** — We have seen that existing glaciers illustrate two widely different types — inland-ice and mountain glaciers — with the small ice-caps in an intermediate and transitional position. As regards the inland-ice, the Arctic and Antarctic continental glaciers differ mainly in degree; the smaller Arctic form being entirely restricted to the land area, whereas the Antarctic ice-mass being more amply nourished is locally extended by a marginal terrace floating upon the sea. Similarly mountain glaciers on the basis of their alimentation fall naturally into a series of sub-types ranging on the one hand from those which spread out beyond the margin of the upland — the piedmont glacier — to those puny forms which in the last stage of a progressive extinction are crowded hard against the mountain summits.

**Physiographic Form.** — As regards their physiographic form the inland-ice masses adhere to a definite model — a flat dome which in the case of the Antarctic example is extended by a lower marginal terrace of shelf ice. The mountain glaciers, on the other hand, conform to no regular model, but have a relief directly determined by the forms of the supporting upland. In respect to form, the ice-cap is allied to the inland-ice, having, in common with it, small irregularities in the surface of its supporting base if these be but compared to its general dimensions.

**Denuding Processes.** — As concerns denuding processes mountain glaciers are in common with inland-ice characterized by the capacity to lower the level of their beds through the operation of the processes of abrasion and plucking; but they have in addition the power to denude rapidly by cirque recession — extraordinarily rapid sapping through daily summer frost work at the base of the bergschrund. Whereas inland-ice reduces the irregularities and softens the outlines of its rock bed, mountain glaciers by contrast increase the accent of the relief, and, in fact, develop a more sharply rugged topography than does any other known geological process. In respect to denudation, ice-caps are intermediate between the two main glacier types. While their main degradational process is apparently abrasion (plate 34 A) they may, when aided by uplift of the land under specially favorable conditions, develop the sharply peaked mountains known as *tinds*. Unlike the peaks carved by mountain glaciers, these sharp peaks are developed not above the higher but near the lower ice levels (plate 34 B).

**Alimentation.** — In respect to nourishing processes the two main glacier types are no less sharply differentiated. The ice-caps, which in their physiographic form are allied to the inland-ice, are here no less clearly to be classed with mountain glaciers.

Mountain glaciers are nourished by moisture-laden *surface* currents of air, which encountering an upland area are forced to rise, and are thereby cooled adiabatically and by contact with the upland, so that their burden is deposited in the form of snow. Inland-ice, on the contrary, if we neglect for the moment the marginal terrace sometimes present, appears to be regularly fed from *high-level* currents through the operation of a refrigerating air engine of which the ice mass and its atmospheric cover are the essential parts.

Through the rhythmic action of this engine the congealed

*A.* View of the high surfaces of the Jotunheim from the Galdho, showing effect of abrasion beneath ice-cap glaciers (after Fritz Machaček).

*B.* The Maelkevoldsbrae of the Jostefjeld, showing the development of *tinds* about the borders of a Norwegian ice-cap through the erosional work of outlet glaciers (after Fritz Machaček).

moisture derived from the ocean surface within moderate or low latitudes and carried to the polar region in the high level cirrus clouds, is pulled down to the surface of the glacier in the eye of a great glacial anticyclone which is centred above it. During their descent from high levels the ice grains of the clouds are melted and vaporized by adiabatic warming, and on reaching the cold surface layer of air next the ice, are quickly congealed to form flakes of fresh snow. The progressive warming of the air adiabatically both during its descent to the central area of the ice mass and on the further slide outward to the peripheral portions, gradually damps and eventually stops the sliding centrifugal motion of the surface air-layer. Thus the engine comes to rest or, as we may say, has reached the end of its stroke. The great calm which ensues allows heat to be again slowly abstracted from the surface layer of air, thereby lowering its temperature and raising its density until gravity again starts the engine, which now acquires the steadily accelerating velocity characteristic of bodies sliding on inclined planes. The tempest which is eventually engendered is succeeded by a rapid rise of air temperature, a fall of fresh snow, and another stopping of the engine.

The fierce violence of the surface air currents when at their maximum, and the fall of the snow for the most part as the engine is slowing down, together make of this glacial anticyclone a gigantic snow broom. The snow deposited as it were between strokes of the engine is by the next sweep of the broom brushed largely clear from all central portions of the glacier, and the sweepings are deposited near and about the margins of the mass (see Figure 140). Since the continental glacier must grow during the advancing hemicycle in a vertical as well as in a horizontal direction, there must be accretions of snow upon the central areas, which layers adhere to the surface so as not to be removed by the

rhythmic engine strokes. Thus are produced the alternating layers of incoherent and marble-like snow which the crude sections of the surface material have revealed. We

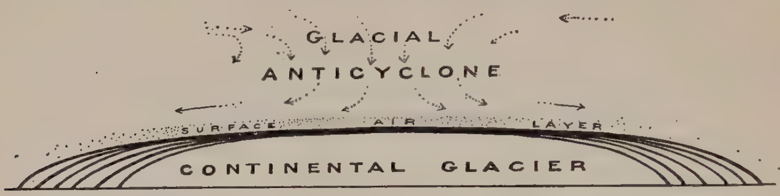


FIG. 140. — Diagram to illustrate the growth of an inland-ice mass through the rhythmic action of the anticyclonic air engine.

are still without sufficient knowledge of the conditions which give rise to the coherent layers. In this manner, then, the great glacier is enlarged and shaped through periodic deposit of snow in successive layers upon its surface but especially by more frequent deposit of sweepings about its margin. This process plays no part in the shaping of mountain glaciers.

The marginal shelf ice appears to be in some cases at least partially nourished by the overflow of glacier ice from the neighboring continental area, but more largely it is fed through the continued thickening of field ice — the frozen sea surface — by deposits of precipitated snow upon its surface. To this precipitated snow there is added a portion of the sweepings carried outward from the surface of the inland-ice. That portion of the nourishment which is derived from glacier overflow at its inner margin, becomes covered by the surface deposits, and so is segregated toward its lower and inner margins.

The formation of shelf ice is greatly favored in more or less sheltered bights from which the sea ice is less easily dislodged and hence does not take part in the annual drift of the pack toward lower latitudes. Further it is locally favored by the stranding or freezing into the sea ice of a fleet of icebergs

from the areas of inland-ice; since these furnish lanes between them within which snow sweepings are more easily caught and retained.

**Marginal Contours.** — As concerns the moulding of surface contours at the glacier margin, the determining factors in the case of mountain glaciers seem to be an upturning of the ice layers in this region and surface ablation or melting. In the case of inland-ice the important factor is the deposition upon the surface of snow borne by the wind from the interior of the mass.

# INDEX

71-1
72-1
73-1